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FOR THE TECHNOLOGY INSIDER | 11.19

The Hydrogen-Powered Farm

How a retired aerospace worker reengineered his own farm to slash its carbon footprint P. 30

IEEE

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On the cover
Illustration for *IEEE Spectrum* by Eddie Guy

3D-PRINTING A ROCKET

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ILLUSTRATION BY Tavis Coburn

AFTER MARIA

SARA IRIZARRY

IN RESEARCH, sometimes the investigator becomes part of the experiment. That's exactly what happened to Efraín O'Neill-Carrillo and Agustín Irizarry-Rivera, both professors of electrical engineering at the University of Puerto Rico Mayagüez, when Hurricane Maria hit Puerto Rico on 20 September 2017. Along with every other resident of the island, they lost power in an islandwide blackout that lasted for months.

The two have studied Puerto Rico's fragile electricity infrastructure for nearly two decades and, considering the island's location in a hurricane zone, had been proposing ways to make it more resilient.

They also practice what they preach. Back in 2008, O'Neill-Carrillo outfitted his home with a 1.1-kilowatt rooftop photovoltaic system and a 5.4-kilowatt-hour battery bank that could operate independently of the main grid. He was on a business trip when Maria struck, but he worried a bit less knowing that his family would have power.

Irizarry-Rivera [top] wasn't so lucky. His home in San Germán also had solar panels. "But it was a grid-tied system," he says, "so of course it wasn't working." It didn't have storage or the necessary control electronics to allow his household to draw electricity directly from the solar panels, he explains.

"I estimated I wouldn't get [grid] power until March," Irizarry-Rivera says. "It came back in February, so I wasn't too far off." In the meantime, he spent more than a month acquiring and installing batteries, charge controllers, and a new stand-alone inverter. His family then relied exclusively on solar power for 101 days, until grid power was restored.

In this issue, the two engineers describe how Puerto Rico could benefit from community microgrids made up of similar small PV systems. The amount of power they produce wouldn't meet the average Puerto Rican household's typical demand. But, Irizarry-Rivera points out, you quickly learn to get by with less.

"We got a lot of things done with 4 kilowatt-hours a day," he says of his own household. "We had lighting and our personal electronics working, we could wash our clothes, run our refrigerator. Everything else is just luxuries and conveniences." ■

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Ottó Elíasson

Elíasson, a physics graduate student at Denmark's Aarhus University, works with the ScienceAtHome project, which invites volunteers to play an online game to advance quantum computing. "I was fascinated by the human ability to solve complex problems," he says, "and the idea to apply it to push the boundaries of research." Elíasson and ScienceAtHome colleagues Carrie Weidner, Janet Rafner, and Shaeema Zaman Ahmed describe how the project works in this issue [p. 36].

Greg Mably

Mably is a Toronto-based illustrator whose work is known for its grid-based compositions and geometric shapes, reflecting what he calls a "mid-20th-century graphic design and modern art sensibility." For this issue, he depicted how online games can further research [p. 36] and why scaling up wind turbines is hard [p. 20]. "I've learned so much about technology from illustrating articles in *Spectrum*," Mably says. "I'm good at cocktail parties because I can talk about so many different things."

Bryce Salmi

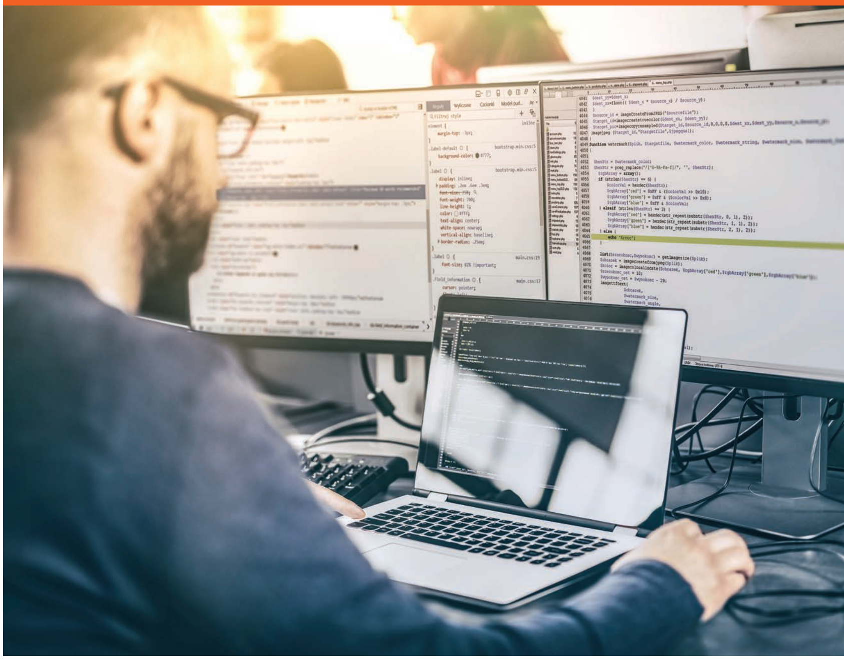
Salmi, lead avionics hardware engineer for the Los Angeles aerospace startup Relativity Space, loves the challenge of sending electronics into the harsh environment of space–where, he says, they really shouldn't go. In this issue, he writes about Relativity's progress toward 3D-printing an entire rocket [p. 22]. When its first vehicle blasts off and the electronics he designed soar toward orbit, "I'm going to shed some tears," says Salmi. "I get very attached."

Jay Schmuecker

After a long career working on planetary spacecraft at NASA's Jet Propulsion Laboratory, Schmuecker turned his attention to farming. At Pinehurst Farm in eastern Iowa, he is developing a demonstration of a solar-hydrogen fueling and fertilization system, as he explains in "The Carbon-Free Farm" [p. 30]. In the process, he's discovered that reengineering farming isn't very different from building spacecraft–they both require a lot of trial and error.

Lawrence Ulrich

In this issue, *IEEE Spectrum* contributing editor Ulrich reports on a new, more powerful electric motor [p. 10]. As an auto writer, he tests more than 80 cars a year. He puts sports cars through their paces at the Monticello (N.Y.) Motor Club. When he's reviewing a minivan, he drives it around town to see how it fits into daily life. "You're really just trying to live with the car," Ulrich says. "You learn a lot about cars when you're stuck in traffic."



For AI Rollouts, Hazards Reported Ahead

Getting machine learning to work is made a lot harder by HR and IT issues

Implementing machine learning in the real world isn't easy. The tools are available and the road is well marked—but the speed bumps are many. ¶ That was the conclusion of panelists at the IEEE AI Symposium 2019, held at Cisco's San Jose, Calif., campus in September. ¶ The toughest problem, says Ben Irving, senior manager of Cisco's strategy innovations group, is people. ¶ It's tough to find applicants with expertise in data science, he indicated, so companies are looking into nontraditional sources of personnel, like political science. "There are some untapped areas with a lot of untapped data-science expertise," Irving says. ¶ Lazard managing director Trevor Mottl agreed that would-be data scientists don't need formal training or experience to break in. "This field is changing really rapidly," he says. "There are new language models coming out every month, and new tools, so [anyone should] expect to not know everything. Experiment, try out new tools and techniques, read; there aren't any true experts at this point because the foundational elements are shifting so rapidly." ¶ "It is a wonderful time to get into a field," he said, noting that it doesn't take long to catch up "because there aren't 20 years of history." ¶ Confusion about what different kinds of machine-learning specialists do doesn't help the personnel situation. An audience member asked panelists to explain the difference between a data scientist, a data analyst, and a data engineer. Darrin Johnson, Nvidia global director of technical marketing for enterprise, admitted it's hard to sort out, and any two companies could define the positions differently. ¶ The competition to hire data scientists, analysts, engineers, or whatever companies call them requires that managers make sure that any work being done is structured and comprehensible at all times, the panelists cautioned. ¶ "We need to remember that our data scientists go home every day and sometimes they don't come back, because they go home and then go to a different company," says Lazard's Mottl. "If you give people a choice on [how they do their development] and have a successful person who gets poached by a competitor, you have to either hire a team to unwrap what that person built or jettison their work and rebuild it."

By contrast, he says, "places that have structured coding and structured commits and organized constructions of software have done very well."

And keeping all of a company's engineers working with the same languages and on the same development paths is not easy to do in a field that moves as fast as machine learning.

Once a company finds the data engineers and scientists it needs and gets them started applying machine learning to the company's operations, one of the first obstacles the company faces just might be its own IT department, the panelists suggested.

"IT is process oriented," Mottl says. IT teams "know how to keep data secure, to set up servers. But when you bring in a data-science team, they want sandboxes, they want freedom, they want to explore and play."

And Nvidia's Johnson pointed out, "There's a language barrier." The AI world, he says, is very different from networking or storage, and data scientists find it hard to articulate their requirements to IT.

Mottl says rolling machine-learning technology into operation can hit resistance from all across a company. And he had one last word of caution for those aiming to implement AI: "Data scientists are building things that might change the ways other people in the organization work. [You need to] think about the internal stakeholders and prepare them because the last thing you want to do is to create a valuable new thing that nobody likes." —TEKLA S. PERRY

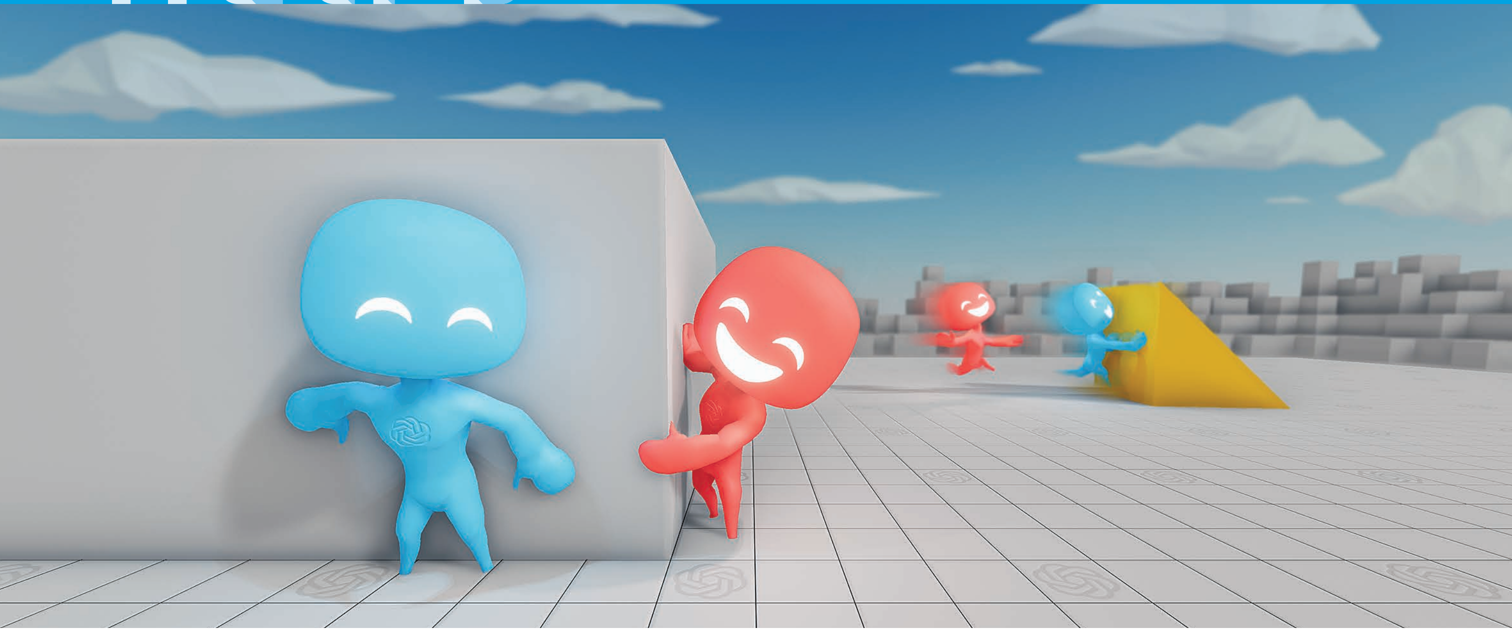
The AI Symposium was organized by the Silicon Valley chapters of the IEEE Young Professionals, the IEEE Consultants' Network, and IEEE Women in Engineering and supported by Cisco. A version of this article appears in our View From the Valley blog.

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/rollouts1119

CORRECTION: In "When Apps Rule the Road" [October 2019], we erred in stating that "an estimated 1 billion drivers use such apps in the United States alone." This figure actually refers to usage worldwide.

ISTOCKPHOTO

NEWS



AI AGENTS PLAY HIDE-AND-SEEK

An OpenAI project demonstrated "emergent behavior" by AI players

After 25 million games, the AI agents playing hide-and-seek with each other had mastered four basic game strategies. The researchers expected that part.

But after a total of 380 million games, the AI players developed strategies that the researchers didn't know were possible in the game environment. That was the part that surprised the team at OpenAI, a research company based in San Francisco.

The AI players learned everything via a machine-learning technique known as reinforcement learning. In this learning method, AI agents start out by taking random actions. Sometimes those random actions produce desired results, which earn the AI players rewards. Via trial and error on a massive scale, they can learn sophisticated strategies.

In the context of games, this process can be abetted by having the AI play against another version of itself, ensuring that the opponents will be evenly matched. It also locks the AI into a process of one-upmanship, where any new strategy that emerges forces the opponent to search for a countermeasure. Over time, this "self-play" amounts to what the researchers call an "auto-curriculum."

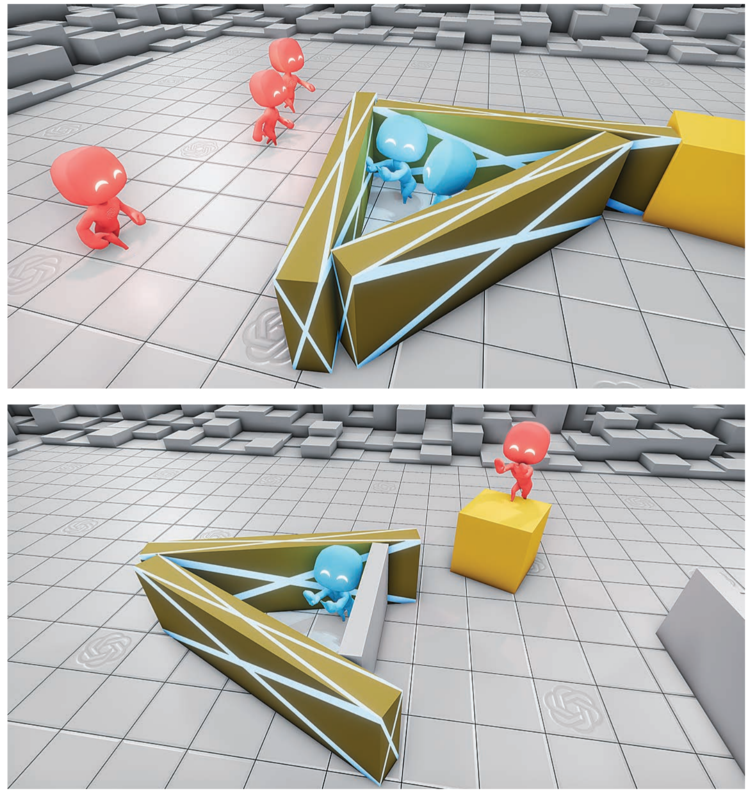
According to OpenAI researcher Igor Mordatch, this experiment shows that self-play "is enough for the agents to learn surprising behaviors on their own—it's like children playing with each other."

Reinforcement learning is a hot field of AI research right now. The OpenAI team used the technique when they trained bots to play the video game *Dota 2*. That team of bots squashed a world-champion human team last April. The Alphabet subsidiary DeepMind used it to triumph in the ancient board game Go.

OPEN AI

Aniruddha Kembhavi, a researcher at the Allen Institute for Artificial Intelligence (AI2) in Seattle, says games such as hide-and-seek offer a good way for AI agents to learn "foundational skills." He worked on a team that taught an AI to play Pictionary with humans, viewing the gameplay as a way for the AI to work on commonsense reasoning and communication. "We are, however, quite far away from being able to translate these preliminary findings in highly simplified environments into the real world," says Kembhavi.

In OpenAI's game of hide-and-seek, both the hiders and the seekers received a reward only if they won the game, leaving the AI players to develop their own strategies. Within a simple 3D environment containing walls, blocks, and ramps, the players first learned to run around and chase each other. Next, the hiders learned to move the blocks around to build forts, and then the seekers learned to move the ramps, enabling them to jump inside the forts. Then the hiders learned to move all the ramps into their forts before the seekers could use them.



NEW TRICKS: Blue AI agents build a fort [top] to keep opponents out. A red agent uses a box to "surf" into the fort [bottom] during a game developed by OpenAI.

The two strategies that surprised the researchers came next. First the seekers learned that they could jump onto a box and "surf" it over to a fort, allowing them to jump in—a maneuver that the researchers hadn't realized was physically possible in the game environment. So as a final countermeasure, the hiders learned to lock all the boxes into place so they weren't available for use as surfboards.

In this circumstance, having AI agents behave in an unexpected way wasn't a problem—they found different paths to their rewards, but didn't cause any trouble. However, you can imagine situations in which the outcome would be rather serious. Consider Nick Bostrom's famous example of a paper clip factory run by an AI, whose goal is to make as many paper clips as possible. As Bostrom told *IEEE Spectrum* back in 2014, the AI might realize that "human bodies consist of atoms, and those atoms could be used to make some very nice paper clips."

Bowen Baker, another member of the OpenAI research team, notes that it's hard to predict all the ways an AI agent may act inside an environment—even a simple one. "Building these environments is hard," he says. "The agents will come up with these unexpected behaviors, which will be a safety problem down the road when you put them in more complex environments."

AI researcher Katja Hofmann at Microsoft Research Cambridge, in England, has seen a lot of gameplay by AI agents: She started a competition that uses *Minecraft* as the playing field. She says the emergent behavior seen in this game, and in prior experiments by other researchers, shows that games can be a useful tool for studies of safe and responsible AI.

"I find demonstrations like this, in games and gamelike settings, a great way to explore the capabilities and limitations of existing approaches in a safe environment," says Hofmann. "Results like these will help us develop a better understanding on how to validate and debug reinforcement learning systems—a crucial step on the path towards real-world applications."

Baker says there's also a hopeful takeaway from the surprises in the hide-and-seek experiment. "If you put these agents into a rich enough environment, they will find strategies that we never knew were possible," he says. "Maybe they can solve problems that we can't imagine solutions to."

—ELIZA STRICKLAND

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

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/hideandseek1119

AT LAST, A MASSIVE SOLAR PARK FOR EGYPT

A 1.8-GW, $4 billion solar power plant is coming on line in the Sahara

Amid the sand dunes of the eastern Sahara, workers are putting the finishing touches on one of the world's largest solar installations. There, as many as 7.2 million photovoltaic (PV) panels make up Benban Solar Park—a renewable energy project so massive, it's visible from space with the naked eye.

The 1.8-gigawatt installation is the first utility-scale PV plant in Egypt, a nation blessed with some of the world's best solar resources. The ambitious project is part of Egypt's efforts to increase its generation capacity and incorporate more renewable sources into the mix.

"I think Benban Solar Park is the first real step to put Egypt on the solar production world map," says Mohamed Orabi, a professor of power electronics at Aswan University.

To create the park, Egypt's government selected a remote desert site and assigned 41 plots to roughly 30 developers, promising to pay a competitive price for all power produced there for 25 years. With loans from International Finance Corp. and the World Bank, the state-owned electricity company built four substations, a control center, and a connection to nearby 220-kilovolt transmission lines. The developers, which include Alcazar Energy Partners and Shapoorji Pallonji Group, installed panels, transformers, and inverters. Electricity travels from the panels on each plot to substations through 22-kV cables buried in the sand.

Mohamed Elsheikh, a contractor, says the desert site now looks like "a big ocean" of photovoltaics. Orabi, who has consulted on projects at the park, said in September that more than 80 percent of installations were complete. Construction has been mostly smooth, despite delays in installing the substations and some issues with the site's automated control system that have forced it into manual operation for the time being.

Ibrahim Helal, an electrical consultant in Cairo, says that the area's high temperatures—which frequently top 38 °C in summer—could affect the site's many inverters, which convert the DC power produced by the panels to the AC power required for the grid.

Elsheikh, head of the electrical department at contractor Emeco, says Schneider Electric did have to repair one inverter after its cable connection overheated. But, he says, such problems were rare.

Sand or dust that blows onto the panels can reduce their efficiency. To combat that, employees will clean all the panels at Benban once or twice a month using specialized tractors equipped with brushes.

Egypt began laying the groundwork for the US $4 billion project after enduring blackouts that reached their worst point in August 2014. At the time, peak demand was 28 GW, but the country's electricity production was limited to just 24 GW. Egypt's government began planning Benban and signed a deal with Siemens to construct three new gas-fired power plants, each with a capacity of 4.8 GW.

Helal believes these investments position Egypt well for its future. "Egypt now is growing very fast," he says. "Even though it may look at the moment like we have a huge reserve of energy, I believe in the forthcoming few years this will be consumed."

Orabi thinks the next step should be to invest in energy storage to ensure the power produced at Benban is put to good use and used to prevent grid fluctuations.

AHMED GOMAA/XINHUA/ALAMY

NEWS

SUN POWER: Renewable energy firm TBEA Sunoasis installed these photovoltaic panels at Benban Solar Park [left]. Employees of the firm monitor power production from the site [right].

Egypt's government has set a goal for 20 percent of the nation's electricity to come from renewable sources by 2022. In 2016, the amount was about 9 percent—mostly from dams along the Nile River. Benban will avoid 2 million metric tons of CO_2 emissions per year compared with those of a thermal power station generating the same amount of electricity.

Orabi says the project has played three important roles in helping solar claim a greater share of Egypt's electricity supply. First, the project drove down the cost of PV systems in Egypt. Second, it proved that solar could be a viable energy source despite several failed concentrated-solar projects. And lastly, it granted more than 3,000 Egyptians who worked at the site valuable experience in installing PV systems.

Benban was the first utility-scale solar PV project that Elsheikh had ever managed. He says Benban has inspired plans for more utility-scale solar PV projects in Egypt.

"We have now a lot of interest," he says. "I'm so proud that I worked on this."
—AMY NORDRUM

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

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/egyptsolar1119

CHINA GREW TWO LEAVES ON THE MOON

The Chang'e-4 spacecraft also carried potato seeds and fruit-fly eggs to the lunar far side

The team behind a pioneering biological experiment sent to the lunar far side recently released an image showing two green leaves grown on the moon. The experiment began shortly after China's Chang'e-4 spacecraft made the first ever landing on the far side of the moon, on 3 January this year. Plants have been grown in low Earth orbit on the International Space Station, but this experiment marked the first time a seed sprouted on the moon.

Cotton, *Arabidopsis thaliana*, and potato seeds, and fruit-fly eggs and yeast were all aboard the 2.6-kilogram mini biosphere, but only the cotton produced positive results. The image the team released this past September is a 3D reconstruction based on image processing and data analysis. That reconstruction has now shown that two cotton leaves had grown—rather than just one as initially thought—in what was the first biological growth experiment on the moon.

All the organisms died with the onset of the first lunar night, with no power to protect the canister from temperatures that reached as low as -190 °C. The cotton leaves were dead within one lunar daytime, or around 14 Earth days.

The experiment continued until May, however, in order to test the longevity of the apparatus. The Chang'e-4 lander and rover, meanwhile, have just started their 11th lunar day in the Von Kármán crater.

Xie Gengxin of the Advanced Technology Research Institute at Chongqing University, who led the design of the experiment, says he and the team are now writing scientific papers based on the results.

Xie says the team initially wanted to send a species of small tortoise on the voyage, but the mission constraints were too great. "The weight of

CHONGQING UNIVERSITY

SPACE PLANTS: The cotton leaves shown in this 3D reconstruction grew on the moon.

the Chang'e-4 probe demanded that the weight [of the experiment] can't exceed 3 kilograms," he says.

The experiment had a pressure of one atmosphere. It was integrated with the spacecraft two months ahead of launch and spent another month in space before landing.

"Even though it is very meaningful to choose [a] tortoise, the oxygen inside the payload can only be used for about 20 days for turtles," Xie says, in explaining why the idea was dropped.

Tortoises have been on moon missions before. The 1968 Soviet Zond 5 mission, in which the spacecraft was the first to circle the moon and safely return to Earth, carried two specimens of the steppe tortoise (also known as Horsfield's tortoise).

However, a lander mission would provide observations of the effects of the moon's gravity–which is one-sixth Earth's gravity–on the animals. Such data would be useful as space agencies consider long-term human missions to the moon.

Xie says the team is proposing to send biology payloads on future missions, and a larger payload allocation might allow more-complex animals to ride along. Following the Chang'e-4 experiment, a number of space agencies from around the world have expressed interest in cooperating with Chongqing University.

Chang'e-6, a Chinese lunar-sample return mission scheduled for the early 2020s, has a small allocation for science experiments, which was opened to national and international proposals. China, the United States, Russia, India, the European Space Agency, and Japan, as well as a range of private companies, are all developing future robotic and human lunar-exploration missions.
—ANDREW JONES

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

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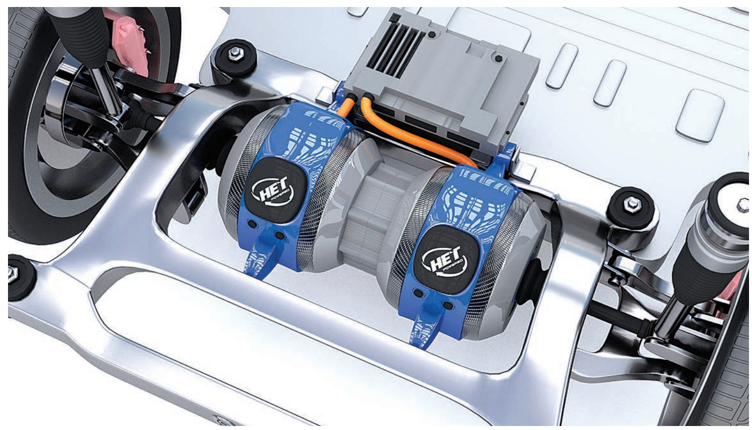
NEWS

STARTUP PROMISES AN ELECTRIC-MOTOR REVOLUTION

Linear Labs says its superefficient motor could power cars, robots, and more



STREAMLINED: The father-son inventors of the Hunstable Electric Turbine say it consumes significantly less energy than other motors of comparable size.

LINEAR LABS

Makers of electric vehicles, e-bikes, or electric scooters—and the owners who love them–tend to focus on batteries, and how much better their vehicles have become as batteries shrink in weight, size, and cost.

But electric motors are the often-overlooked aspect of that equation. Linear Labs says its electric machines could revolutionize automobiles, wind turbines, and air conditioners, as well as robots, drones, and micromobility vehicles.

The Fort Worth, Texas-based company has invented what it calls the Hunstable Electric Turbine, or HET. The patented HET, the company claims, can generate two to five times the torque of existing motors or generators in the same size package. Torque is the amount of work that a motor or engine produces, typically measured on a per-revolution basis.

"We believe we've built an entirely new class of electric motors, and that hasn't happened in maybe 30 years," says Brad Hunstable, the company's founder and chairman.

Hunstable was formerly CEO of UStream, a video streaming and hosting company that IBM acquired for US $150 million in 2016. Brad's father and company chief technical officer, Fred Hunstable, is an inventor and electrical engineer who worked in the nuclear power industry. Linear Labs began about five years ago as a father-and-son project.

The Hunstables tick off the myriad design and technical advantages of their HET, which they define as a 3D circumferential flux, four-rotor permanent-magnet motor. Unlike typical designs, the synchronous DC motor has no superfluous end windings, so 100 percent of its copper material goes into energy conversion. A typical motor's copper content could be reduced by 30 percent while generating equivalent torque, the Hunstables say. So for a given torque level, the HET consumes significantly less energy than competing designs.

Because the magnetic flux (a measure of the total magnetic field that passes through a structure) from the machine's rotor completely engulfs the stator, the Hunstables say, there's virtually no flux leakage. The result is torque that continues to climb while other motor designs begin to plateau. At densities beyond 30 amperes per square millimeter, the Hunstables claim the HET delivers 100 percent more torque than conventional designs.

Martin Doppelbauer, professor of hybrid electric vehicles at Karlsruhe Institute for Technology, in Germany, said that while the idea is intriguing, he's skeptical that it could deliver such dramatic gains in power density. Proper cooling of the HET might be another major challenge, he said.

"It's an interesting approach, but its potential is currently not proven in practice," Doppelbauer said.

Company studies of existing automotive platforms, including the Tesla and the Toyota Prius, show that the motors could increase driving range by more than 10 percent, or allow those cars to carry relatively smaller battery packs to deliver equivalent range. The HET itself, the company claims, can generate up to 150 newton meters of torque at just 3,000 rpm, in a package the size of a Prius's motor.

The motor generates such robust torque that, in most applications, no gearbox reduction is necessary. The system incorporates a purely electronic transmission, which reduces energy losses and, at production scale, could trim at least 45 kilograms (100 pounds) from a vehicle's weight.

Many electrified vehicles must also integrate a DC-to-DC converter–which boosts or chops voltage to varying levels–to enable a full range of driving speeds under various loads. But because the HET can generate more torque at lower rpms, it could also eliminate the boost converter that's found on every car. Thus, the motor could deliver a domino effect that's another holy grail of transportation engineers. A smaller, more efficient motor would allow for lighter batteries, simplified controls, and lighter suspensions.

"The electronics to power motors are often more expensive than the motors themselves," Brad Hunstable says.

Linear Labs has begun working with customers, as yet unnamed, to jointly develop applications for electric and micromobility vehicles, robots, and HVAC systems.

The company says a ride-sharing scooter company asked it to replace a Segway Ninebot ES4 motor with the HET. The resulting Segway had a 50 percent increase in range and four times the torque, which boosted the vehicle's top speed and allowed it to climb a 20 percent grade.

"You'll see us in a micromobility application, with air-cooled motors, within one year," Fred Hunstable says.

The Hunstables add that with 45 percent of the world's electricity eventually flowing through an electric motor, gains in power and efficiency could have untold benefits. One example: The company estimates that, in a large, 8-megawatt wind turbine, the HET could save 80 metric tons of weight and millions of dollars in costs, and raise efficiency by 3 percent.

"We feel we're part of a smarter, cleaner energy movement, with applications way beyond mobility," Brad says.
—LAWRENCE ULRICH

A version of this article appears in our Cars That Think blog.

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/newmotor1119

JOURNAL WATCH

Saltwater Antenna Steers Radio Beams

Most antennas are made of metal. That means they're easy to spot with radar. But what if a gadget needs to be more discreet?

Researchers from Nanjing University of Aeronautics and Astronautics, in China, have built a transparent antenna that steers radio waves with salt water.

The plastic antenna consists of 13 acrylic tubes that can be filled with salt water to transmit signals, and then drained and deflated when not in use. A copper disk feeds a signal into the base of one tube, which stands at the center of a ground plane. The other 12 tubes encircle it.

When only the center tube is excited, the antenna broadcasts in all directions. But when filled with water, the other tubes can be harnessed as reflectors, creating an additional 12 directional phases of broadcast signals. By shifting the surrounding tubes around in a circle, the antenna can send signals in any direction. It works for frequencies between 334 and 488 megahertz.

Micropumps control the water level in the tubes—which Lei Xing, who led the research, says was the hardest part of making the device. Her team describes its work in *IEEE Antennas and Wireless Propagation Letters.*

One limitation of such antennas, Xing notes, is that the permittivity of salt water—a measure of how it interacts with electric fields—is sensitive to temperature. She plans to develop more liquid antennas that can overcome this obstacle. —**MICHELLE HAMPSON**

An extended version of this article appears on our website under Journal Watch.

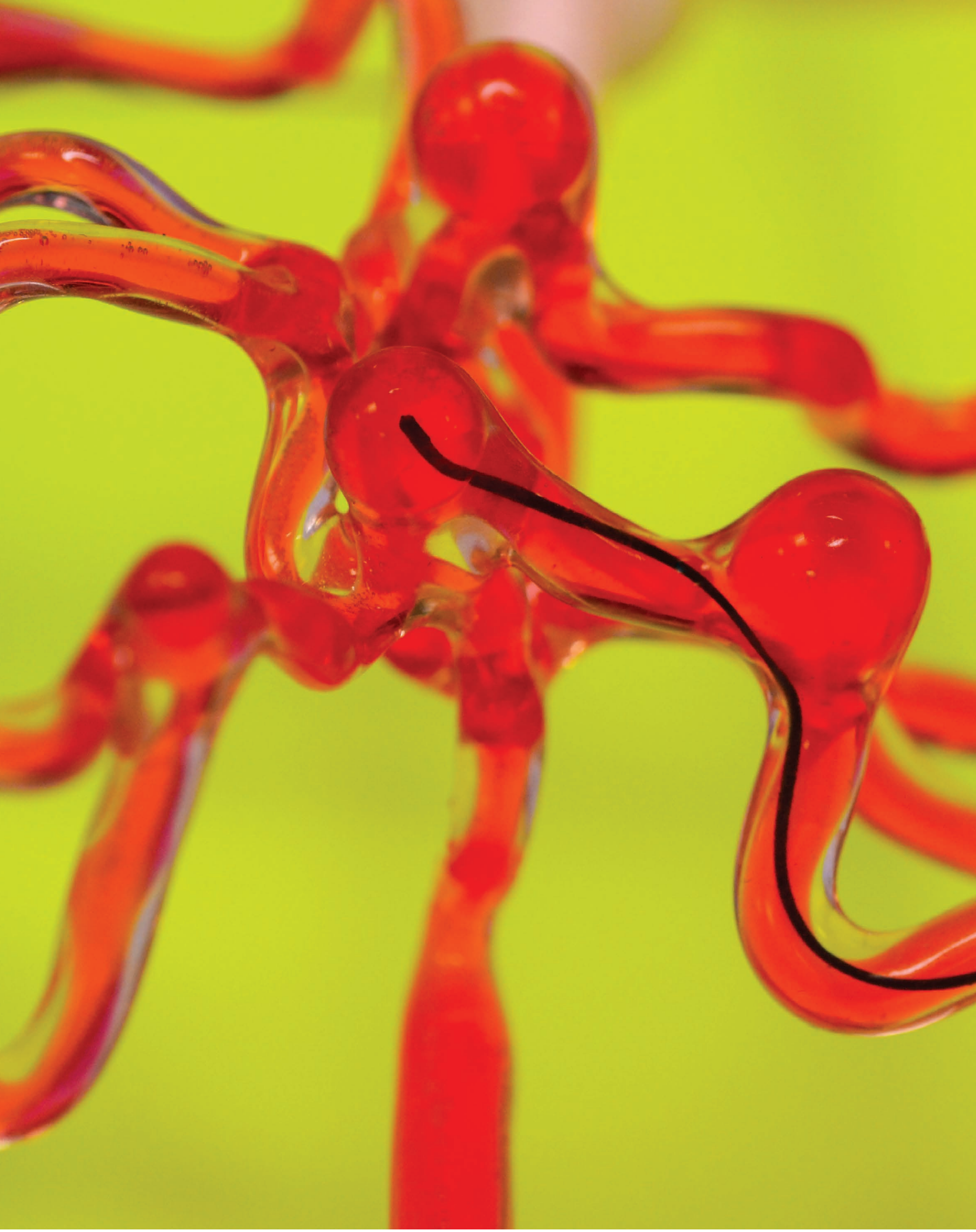


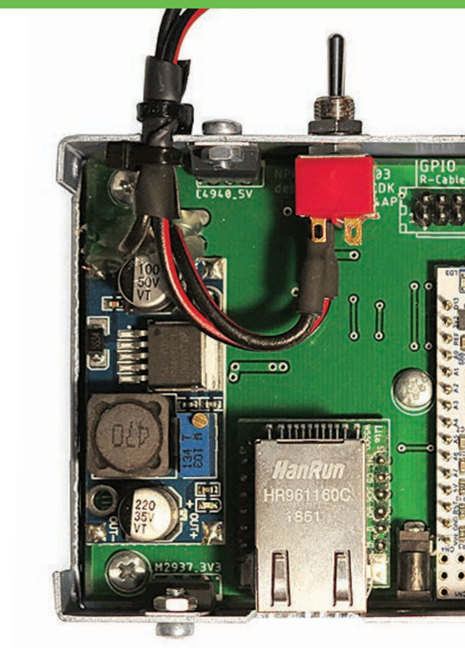
IMAGE BY MIT

MIND GAMES

WHO SAYS PLAYING video games addles the brain? In the near future, brain surgeons could actually save lives by gaming at work. That's because MIT engineers have now created a threadlike robot capable of snaking through blood vessels inside the brain. Surgeons may one day perform delicate operations inside the skull using a joystick to remotely control the robotic thread and steer it to an aneurysm or a stroke-inducing clot. Maneuvering the thread through a maze of blood vessels—like playing a biomedical version of *Pac-Man*—is an improvement over procedures that require the repeated use of X-rays to show a surgeon how to reach a trouble spot in a patient's gray matter. The advance could also allow clinicians to deliver drugs to where they'll be most effective.

RESOURCES


1



HAM RADIO DOES DISTANT DATA NETWORKING

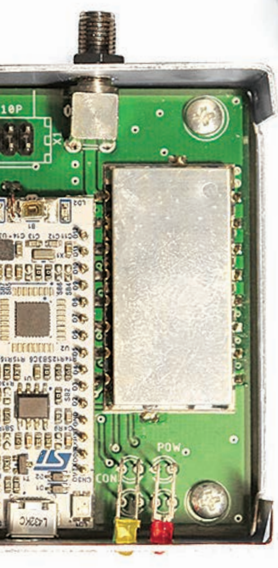
A NEW PROTOCOL RUNS ON SIMPLE HARDWARE AND SUPPORTS IPv4

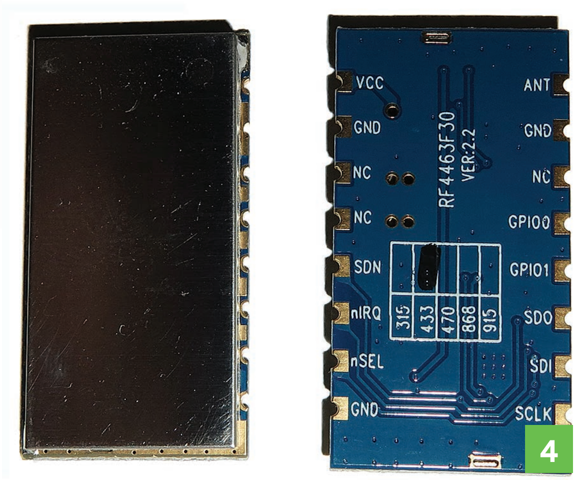
RESOURCES_HANDS ON

I HAVE BEEN A HOBBYIST AND MAKER FOR ALMOST 15 years now. I like inventing things and diving into low-level things. In 2013, I was looking at a protocol called NBP, used to create a data network over amateur radio links. NBP was developed in the 2000s as a potential replacement for the venerable AX.25 protocol that's been in use for digital links since the mid-1980s. I believed it was possible to create an even better protocol with a modern design that would be easier to use and inexpensive to physically implement. ● It took six years, but the result is New Packet Radio (NPR), which I chose to publish under my call sign, F4HDK, as a nom de plume. It supports today's de facto universal standard of communication—the Internet's IPv4—and allows data to be transmitted at up to 500 kilobits per second on the popular 70-centimeter UHF ham radio band. Admittedly, 500 kb/s is not as fast as the megabits per second that flow through amateur networks such as the European Hamnet or U.S. AREDN, which use gigahertz frequencies like those of Wi-Fi. But it is still faster than the 1.2 kb/s normally used by AX.25 links, and the 70-cm band permits long-distance links even when obstructions prevent line-of-sight transmissions.

Initially, I considered using different frequency bands for the uplink and downlink connections: Downlinks would have used the DVB-S standard, originally developed for digital satellite television. Uplinks would have used a variation of FSK (frequency-shift keying) to encode data. But the complexity involved in synchronizing the uplink and downlink was too high. Then I tried using a software-defined radio equipped with a field-programmable gate array (FPGA). I had

F4HDK





1. **Data links work over the medium-range UHF band, but for the best results, a directional antenna is used.** **2.** **The modem is principally a microcontroller attached to a radio transceiver.** **3.** **An amplifier designed for DMR radio links boosts the signal to required levels.** **4.** **The transceiver is a shielded module built around the Si4463 ISM chip, which operates at 434 megahertz.**

some experience with FPGAs thanks to a previous project in which I had implemented a complete custom CPU using an Altera Cyclone 4 FPGA. The goal was to do all the modulation and demodulation using the FPGA, but again the method was too complex. I lost almost two years chasing these ideas to their dead ends.

Then, in one of those why-didn't-I-think-of-this-earlier moments, I turned to ISM (industrial, scientific, and medical) chips. These are transceivers designed to operate in narrow radio frequency bands that were originally allocated for noncommunication purposes, such as RF heating. However, the ISM band has become popular for communications as well because typically a license is not required for its use. In Africa, Europe, and North Asia, there is an ISM band lying inside the 70-cm ham radio band at 434 megahertz, so commercial ISM chips are available for this frequency.

I chose to build my hardware around the Si4463 ISM transceiver: It's cheap, flexible, and available in many modules and breakout boards, and it can handle a raw data rate up to 1 megabyte per second. It's designed for short-range applications, so the radio part of the chip is not optimal, but it works. In order to reach reasonable distances, you need an amplifier to provide more RF power. For my NPR plan, I needed an amplifier that can also switch very rapidly between transmitting and receiving. I found some widely available external 20-watt amplifiers for handheld radios designed for the European-developed Digital Mobile Radio (DMR) standard, which was ratified in 2005. In the DMR standard, radio equipment must be able to handle a complete transmit/receive cycle within 60 milliseconds. I established a minimum of an 80-ms-long cycle time for NPR with this bound in mind.

The ISM transceiver is connected to an Mbed Nucleo STM32 L432KC microcontroller, which uses an Arm Cortex CPU.

This microcontroller is in turn connected to an Ethernet interface, and it takes care of all the details of running the NPR protocol. Any connected PC or network sees the radio link as just another IPv4 connection with no need to install specific NPR software. The NPR modem can be configured over this link or via a USB connection. The total cost of the hardware is about US $80, and a partner, Funtronics, will be making kits available for purchase online. If you want to build a modem yourself from scratch, detailed instructions and the NPR protocol software are available from my Hackaday project page.

The NPR protocol is based on a hub-and-spoke model, in which a central modem links several client modems. Currently there can be as many as seven modems, although I plan to expand this to 15. The theoretical maximum distance between a client modem and the central modem is 300 kilometers. This limit arises because NPR uses a managed time-division multiple access (TDMA) technique, in which the central modem and the clients each transmit on the same frequency but at different times, with the central modem dictating when each client can transmit, and making scheduling adjustments to account for time delays due to distance. The complete transmit/receive cycle is between 80 ms and 200 ms, depending on the exact type of modulation and data rate chosen.

The creation of the NPR protocol was a very fun part of the project for me: deciding how data should be packed and arranged inside radio frames and how the NPR modems should interact with each other. But after two more years it was time to stop working alone, so I shared NPR with my local ham radio community in France. By the end of 2018, we began testing it in real-world conditions. We have already achieved distances over 80 km, and I am now getting help from the global amateur community, especially in Germany. Currently, NPR is primarily being used to access existing local high-speed amateur radio networks from places that cannot have the line-of-sight radio links required for 2.4- and 5.6-gigahertz signals.

Although it's usable, I would be the first to admit that NPR is a young technology and probably not totally mature. In addition to increasing the number of clients that can be supported by a central modem, I have a number of enhancements in mind, such as adding support for QoS (quality of service) prioritization, so that NPR could be used to transmit digital voice; allowing Ethernet frames to be transported directly; and separating downlink and uplink frequencies. **—F4HDK**

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/NPR1119

WHERE TECHIES WANT TO WORK

AIRBNB, GOOGLE, AND SPACEX TOP THE RANKINGS

IT'S THE SALARY. AND THE location. And the mission. And the reputation. It's a combination of these things—as well as, let's face it, the coolness factor—that make a tech company a dream employer for a software engineer, product manager, data scientist, or other tech professional.

Job search firm Hired surveyed 3,600 tech professionals to come up with a list of top employers. It did this by creating a positivity index—a number based on a mix of survey respondents who either would "love to work" or "might like to work" at a particular company. Some of the usual suspects—Apple, Facebook, Google, Microsoft—made the top 15. But others, particularly on the list of privately held tech companies—were a bit of a surprise. I didn't realize engineers dreamed of working at Virgin Hyperloop One or Instacart; and stock-trading app Robinhood hadn't even been on my radar until it ranked seventh on LinkedIn's list of hottest startups released in September.

Silicon Valley companies dominated the dream employer rankings—of the top 30 (15 publicly traded, 15 private) companies that Hired identified, 19 call the San Francisco Bay Area home. And in spite of this being a global survey, no non-U.S. company made the rankings. Another common factor was the youth of the companies: The median age of the private companies is 10 years, while for the public ones it's 16. However there are two notable outliers: NASA and Caltech's 83-year-old interplanetary robotic exploration organization, JPL, is No. 13 in the private ranking, while at No. 14 among the public companies is the Walt Disney Co., age 96. **—TEKLA S. PERRY**

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

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/topemployers1119

ISTOCKPHOTO

COMPANIES MOST LOVED BY TECH PROFESSIONALS

PRIVATE

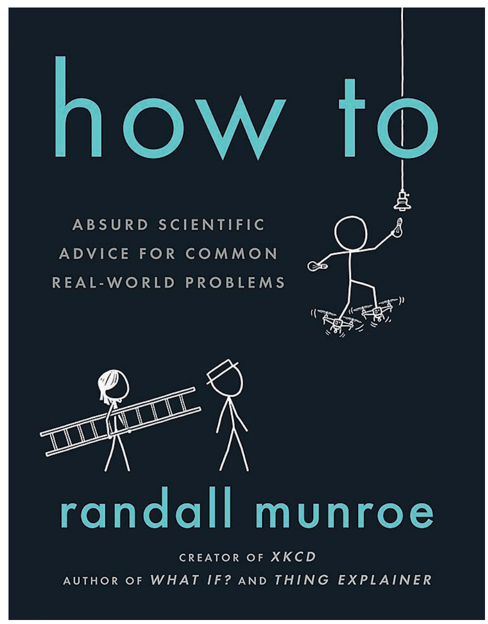
Rank	Company	Location	Year founded
1	Airbnb	San Francisco Bay Area	2008
2	SpaceX	Los Angeles Area	2002
3	Hulu	Los Angeles Area	2007
4	Reddit	San Francisco Bay Area	2005
5	Kickstarter	New York City	2009
6	WeWork	New York City	2010
7	Indeed	Austin, Texas	2004
8	Robinhood	San Francisco Bay Area	2013
9	Stripe	San Francisco Bay Area	2010
10	Squarespace	New York City	2003
11	Virgin Hyperloop One	Los Angeles Area	2014
12	Quora	San Francisco Bay Area	2009
13	JPL	Los Angeles Area	1936
14	Instacart	San Francisco Bay Area	2012
15	Coinbase	San Francisco Bay Area	2012

PUBLIC

Rank	Company	Location	Year Founded
1	Google	San Francisco Bay Area	1998
2	Netflix	San Francisco Bay Area	1997
3	Apple	San Francisco Bay Area	1976
4	LinkedIn	San Francisco Bay Area	2003
5	Microsoft	Seattle Area	1975
6	Slack	San Francisco Bay Area	2009
7	Amazon	Seattle	1994
8	GitHub	San Francisco Bay Area	2008
9	Dropbox	San Francisco Bay Area	2007
10	Tesla	San Francisco Bay Area	2003
11	Adobe	San Francisco Bay Area	1982
12	Lyft	San Francisco Bay Area	2012
13	Facebook	San Francisco Bay Area	2004
14	The Walt Disney Co.	Los Angeles Area	1923
15	Twitter	San Francisco Bay Area	2006

RANDALL MUNROE HAS ABSURD ADVICE FOR YOU

THE XKCD CARTOONIST IMAGINES THE LIMITS OF SCIENCE AND TECHNOLOGY



RIVERHEAD BOOKS

RANDALL MUNROE GAINED INTERNET CELEBRITY for his incisive XKCD comic strip, which combines stick figures, infographics, humor, and a deep grounding in science and technology. Two of Munroe's previous books, *What If?* and *Thing Explainer*, both from Houghton Mifflin Harcourt, became best sellers, and he recently released his latest book, *How To: Absurd Scientific Advice for Common Real-World Problems* (Riverhead Books). In it, he offers hard-won advice in such essential matters as "How to build a lava moat" and "How to catch a drone with sports equipment." (In researching the latter chapter he recruited tennis star Serena Williams to knock a quadcopter out of the air using her powerhouse serves. It took only three tries.)

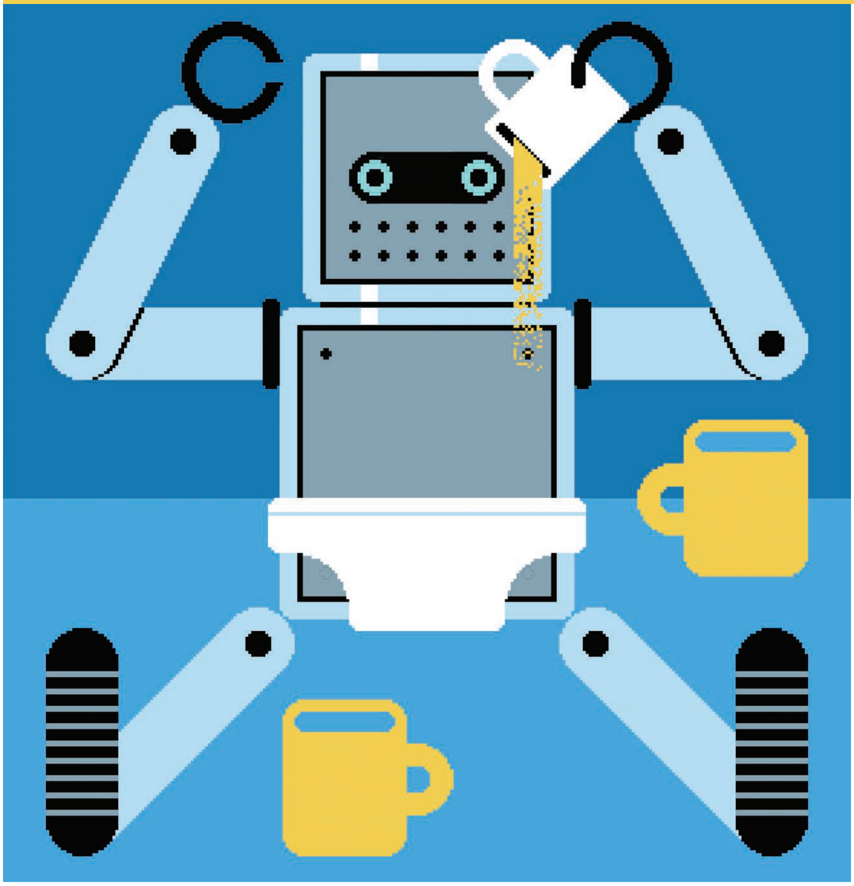
IEEE Spectrum contributing editor Mark Anderson spoke with Munroe in his fortress of solitude somewhere in Massachusetts.

Mark Anderson: You were a physics major in college, right?

Randall Munroe: I had a physics major with a math and computer science minor.

M.A.: Were you much of a doodler as a student?

R.M.: That's actually how I got started doing XKCD. A lot of the early strips I posted were just scans of things from my notebook. I'd post them to share with friends because the notebooks were falling apart. But then they started getting | CONTINUED ON PAGE 49



ROBOTS AS SMART AS BABIES

LET'S FACE IT: ROBOTS ARE DUMB. At best they are idiot savants, capable of doing one thing really well. In general, even those robots require specialized environments in which to do their one thing really well. This is why autonomous cars or robots for home health care are so difficult to build. They'll need to react to an uncountable number of situations, and they'll need a generalized understanding of the world in order to navigate them all. ● Babies as young as two months already understand that an unsupported object will fall, while five-month-old babies know materials like sand and water will pour from a container rather than plop out as a single chunk. Robots lack these understandings, which hinders them as they try to navigate the world without a prescribed task and movement. ● But we could see robots with a generalized understanding of the world (and the processing power required to wield it) thanks to the video-game industry. Researchers are bringing physics engines—the software that provides real-time physical interactions in complex video-game worlds—to robotics. The goal is to develop robots' understanding in order to learn about the world in the same way babies do. ● Giving robots a baby's sense of physics helps them navigate the real world and can even save on computing power, according to Lochlainn Wilson, the CEO of SE4, a Japanese company building robots that could operate on Mars. SE4 plans to avoid the problems of latency caused by distance from Earth to Mars by building robots that can operate independently for a few hours before receiving more instructions from Earth. ● Wilson says that his company uses simple physics engines such as PhysX to help build more-independent robots. He adds that if you can tie a physics engine to a coprocessor on the robot, the real-time basic physics intuitions won't take compute cycles away from the robot's primary processor, which will often be focused on a more complicated task.

Wilson's firm occasionally still turns to a traditional graphics engine, such as Unity or the Unreal Engine, to handle the demands of a robot's movement. In certain cases, however, such as a robot accounting for friction or understanding force, you really need a robust physics engine, Wilson says, not a graphics engine that simply simulates a virtual environment. For his projects, he often turns to the open-source Bullet Physics engine built by Erwin Coumans, who is now an employee at Google.

Bullet is a popular physics-engine option, but it isn't the only one out there. Nvidia Corp., for example, has realized that its gaming and physics engines are well-placed to handle the computing demands required by robots. In a lab in Seattle, Nvidia is working with teams from the University of Washington to build kitchen robots, fully articulated robot hands and more, all equipped with Nvidia's tech.

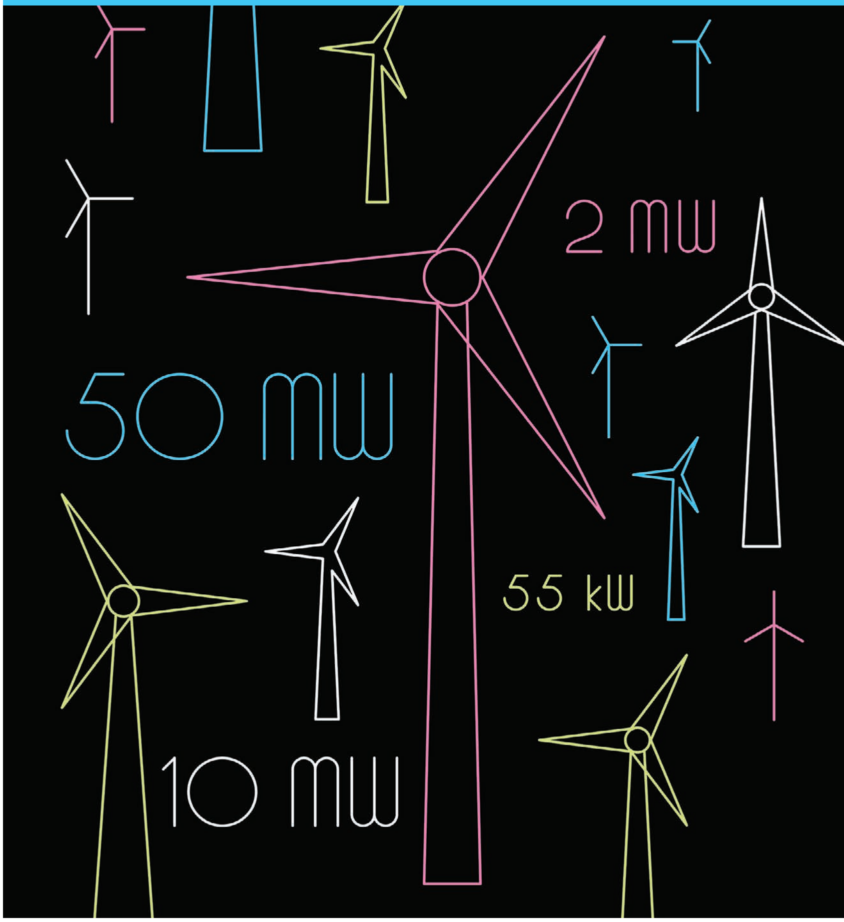
When I visited the lab, I watched a robot arm move boxes of food from counters to cabinets. That's fairly straightforward, but that same robot arm could avoid my body if I got in its way, and it could adapt if I moved a box of food or dropped it onto the floor.

The robot could also understand that less pressure is needed to grasp something like a cardboard box of Cheez-It crackers versus something more durable like an aluminum can of tomato soup.

Nvidia's silicon has already helped advance the fields of artificial intelligence and computer vision by making it possible to process multiple decisions in parallel. It's possible that the company's new focus on virtual worlds will help advance the field of robotics and teach robots to think like babies. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/babyrobots1119

ILLUSTRATION BY Nicholas Little



WIND TURBINES: HOW BIG?

WIND TURBINES HAVE CERTAINLY GROWN UP. When the Danish firm Vestas began the trend toward gigantism, in 1981, its three-blade machines were capable of a mere 55 kilowatts. That figure rose to 500 kW in 1995, reached 2 MW in 1999, and today stands at 5.6 MW. In 2021, MHI Vestas Offshore Wind's V164 will rise 105 meters high at the hub, swing 80-meter blades, and generate up to 10 MW, making it the first commercially available double-digit turbine ever. Not to be left behind, General Electric's Renewable Energy is developing a 12-MW machine with a 260-meter tower and 107-meter blades, also rolling out by 2021. • That is clearly pushing the envelope, although it must be noted that still larger designs have been considered. In 2011, the UpWind project released what it called a predesign of a 20-MW offshore machine with a rotor diameter of 252 meters (three times the wingspan of an Airbus A380) and a hub diameter of 6 meters. So far, the limit of the largest conceptual designs stands at 50 MW, with height exceeding 300 meters and with 200-meter blades that could flex (much like palm fronds) in furious winds. • To imply, as an enthusiastic promoter did, that building such a structure would pose no fundamental technical problems because it stands no higher than the Eiffel tower, constructed 130 years ago, is to choose an inappropriate comparison. If the constructible height of an artifact were the determinant of wind-turbine design then we might as well refer to the Burj Khalifa in Dubai, a skyscraper that topped 800 meters in 2010, or to the Jeddah Tower, which will reach 1,000 meters in 2021. Erecting a tall tower is no great problem; it's quite another proposition, however, to engineer a tall tower that can support a massive nacelle and rotating blades for many years of safe operation.

Larger turbines must face the inescapable effects of scaling. Turbine power increases with the square of the radius swept by its blades: A turbine with blades twice as long would, theoretically, be four times as powerful. But the expansion of the surface swept by the rotor puts a greater strain on the entire assembly, and because blade mass should (at first glance) increase as a cube of blade length, larger designs should be extraordinarily heavy. In reality, designs using lightweight synthetic materials and balsa can keep the actual exponent to as little as 2.3.

Even so, the mass (and hence the cost) adds up. Each of the three blades of Vestas's 10-MW machine will weigh 35 metric tons, and the nacelle will come to nearly 400 tons. GE's record-breaking design will have blades of 55 tons, a nacelle of 600 tons, and a tower of 2,550 tons. Merely transporting such long and massive blades is an unusual challenge, although it could be made easier by using a segmented design.

Exploring likely limits of commercial capacity is more useful than forecasting specific maxima for given dates. Available wind turbine power is equal to half the density of the air (which is 1.23 kilograms per cubic meter) times the area swept by the blades (pi times the radius squared) times the cube of wind velocity. Assuming a wind velocity of 12 meters per second and an energy-conversion coefficient of 0.4, then a 100-MW turbine would require rotors nearly 550 meters in diameter.

To predict when we'll get such a machine, just answer this question: When will we be able to produce 275-meter blades of plastic composites and balsa, figure out their transport and their coupling to nacelles hanging 300 meters above the ground, ensure their survival in cyclonic winds, and guarantee their reliable operation for at least 15 or 20 years? Not soon. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/windturbines1119

ILLUSTRATION BY Greg Mably

ARE SPECIALIST ENGINEERS MORE SUCCESSFUL?

I WAS WALKING MY DOG ONE MORNING WHEN I SAW a man setting up a surveyor's laser transit. I stopped to ask him about it, and the man launched into a long explanation, beginning with "I'm an engineer, so I know about these things." ● I didn't mention that long ago as a college freshman I was required to take a course in surveying. This, as well as drafting, welding, and other forgotten subjects, were deemed to be things that a well-rounded engineer should know. I wasn't very good at some of them, and I despaired at becoming what I thought of as a "real" engineer. ● In later years, I got to know some people who I believed were "real engineers." They knew things. Lots of things, and across a broad swath of technology. And more than just knowing things, they had an instinctive ability to work with or fix anything mechanical or electronic. Often they were, or had been, radio amateurs. ● I think of Thomas Edison as the epitome of a real engineer, but I'm not sure that such people still exist today. My test for being a real engineer is how well you would do as Mark Twain's Connecticut Yankee in King Arthur's Court. How much electrical technology could you create yourself if you were transported back in time to the Middle Ages? Would your electrical magic make Merlin jealous, or would all this end badly? ● I held these generalist engineers in the highest esteem. They were usually the people I would call when some problem arose. But now I am wondering–how successful were they in their overall careers? I was prompted to consider this by reading Thomas Epstein's recent popular book *Range–Why Generalists Triumph in a Specialized World* (Riverhead Books). My immediate reaction to the title was skepticism. Is it true in electrical engineering today that generalists are more likely to succeed than are specialists?

It seems to me that almost all the IEEE major awards go to specialists. IEEE Fellows and members of the National Academy of Engineering get elected because of specialties. Most of the important innovations in our field have been made by specialists. Many of the engineers who have started important tech companies have done so in the field of their specialty. Of course, some of these famous engineers could be real engineers, but their success and fame was initially due to their mastery of a specialty.

Epstein's book is more nuanced than its title would imply. It does say, sometimes grudgingly, that specialists are nice to have, but their weakness is in having a narrow view. They are often most useful as adjuncts to the generalists. But perhaps in engineering it's the other way around–it is generalists who are nice to have, but it is specialists who triumph. Yes, we need and respect real engineers, but the pathway to success seems to lead through specialization. Our world is too complex. The most successful among us begin as specialists. Some of the best then become generalists later, showing innate skills in management, interpersonal skills, communications, and business.

It's an academic argument, literally. Should the education system focus on producing "real engineers," or has our field become so splintered and complex that early specialization is a necessary step to an employable skill? ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/reflections1119

ILLUSTRATION BY Eglė Plytnikaitė

3D-PRINTING a ROCKET

By Bryce Salmi

SIMPLIFY, SIMPLIFY, SIMPLIFY: Relativity Space makes rocket science look easy. Its Aeon engine, shown in side view [opposite] and from the bottom [below], is composed of three 3D-printed parts. A classic rocket engine is assembled from thousands of parts.

Relativity Space is reinventing rocketry with additive manufacturing

I'll never forget the first time I saw a rocket materialize before my eyes.

In October 2018, I stood in a small room and watched a massive robotic arm move elegantly around a large metal shape, which was rapidly growing larger as I gazed at it. The arm precisely deposited a stream of liquid aluminum to build up the structure, layer by layer, while two other arms waited, with finishing tools at the ready. I was standing in the Los Angeles headquarters of the upstart rocket company Relativity Space, staring in awe as a piece of its first launch vehicle, the Terran 1 rocket, came into existence.

I had only recently arrived at Relativity as the first engineer hired for its avionics department. Relativity offered quite a change of scenery from my prior jobs, even though the other companies I'd worked for also built rockets. But they did so in massive rooms, measuring thousands of square meters, enough to hold ranks of bulky manufacturing tools such as metal rollers, dome spinners, and friction-stir welding machines. At Relativity, though, most of the launch vehicle is built inside the small room where I was standing, which measures just 9 meters across.

The room contained Stargate, the largest metal 3D printer in the world. Relativity invented the Stargate printer for the audacious purpose of 3D printing an entire rocket that's intended to fly to low Earth orbit. We hope our rockets will eventually fly even farther. Perhaps one day we'll ship our 3D printers to Mars, so rockets can be constructed on the Red Planet. From there, who knows where they'll go.

Does this sound crazy? Crazy ambitious, maybe. But plenty of people are taking our idea seriously. Four commercial customers have signed up for launches to Earth orbit beginning in early 2021. The U.S. Air Force has approved our request to build a launch site at Cape Canaveral, the famed Florida facility that launched many historic human spaceflight missions. And NASA has leased us a building at its Stennis Space Center, in Bay St. Louis, Miss., where Relativity will build a factory capable of turning out 24 rockets per year. Such mass production will represent a revolution in rocketry. By embracing additive manufacturing—that is, 3D printing—we believe we can pull it off.

LAUNCHING A ROCKET into orbit is a binary proposition: Either you succeed or you fail. During the roughly 10-minute flight from launchpad to space, a mind-boggling array of systems must work together perfectly—plumbing, avionics, software, pyrotechnics, and pneumatics, to name just a few. If any component fails, the whole endeavor can literally come crashing down.

The cost of a rocket is not determined by its raw materials; those are pretty cheap. It's largely driven by the human labor needed to work those materials into usable components and verify that they will function for flight. There are two ways to reduce these labor costs: You can reduce the total number of parts in a rocket so less labor is needed, or you can change manufacturing processes to reduce the need for human minds and hands.

Blue Origin, SpaceX, and Virgin Orbit—companies that are leading the charge in the new commercial space sector—have tried a combination of these two methods to reduce labor costs. But these companies' reliance on traditional "subtractive"

ALL PHOTOS: RELATIVITY SPACE

MADE FROM SCRATCH: Jordan Noone, Relativity Space cofounder, stands in front of the company's newest 3D printer as it builds a fuel tank for the Terran 1 rocket. The additive manufacturing approach makes it easy for Noone's team to iterate on their designs.

manufacturing techniques, in which chunks of raw material are cut down and shaped, limits their options. The companies have automated much of their supply chains, yet they still have tens of thousands of parts to track through complex manufacturing systems. Automating the manufacturing process has reduced human labor, but it requires expensive customized tooling that matches the dimensions of a particular rocket.

Relativity approaches the labor challenge head on by leveraging additive manufacturing to print complex components, using a single operation to turn raw material into finished product. This approach dramatically reduces part count because one of our components is often the equivalent of dozens of small parts made via traditional manufacturing. Our process also relies on our 3D printers rather than fixed tooling, which enables us to be nimble and inventive. We can make large design changes with relatively little cost or time lost.

Rocketry operates on a different scale than other manufacturing sectors. Consider that the Volkswagen plant in Wolfsburg, Germany, turns out about 3,500 vehicles per day. In contrast, any aerospace company that could build 100 rockets in a year would be monumentally successful. What's considered high-volume production in rocketry is relatively low-volume in other industries. That means that additive manufacturing can have a big impact on the industry. Because only dozens or hundreds of a particular part may be needed in a year, it doesn't necessarily make sense to invest in highly optimized tooling to turn out that part in mass quantities—the tools might not pay for themselves before the part becomes obsolete.

Making a new part using a 3D printer requires little to no up-front cost. For example, one of our Stargate printers can produce a 2-meter-diameter propellant tank followed

START TO FINISH: Above, engineers keep an eye on the printing process, which is highly automated. Opposite, cofounders Tim Ellis [left] and Jordan Noone inspect a finished product: the Terran 1 rocket's second stage, composed of a fuel tank, engine, and nozzle extension.

by a 3-meter-diameter tank with minimal downtime. Rather than having to retool an entire manufacturing facility to fabricate the next piece of hardware in the queue, we have to make only a few software-configuration changes.

OUR COMPANY'S cofounders, Jordan Noone and Tim Ellis, met in college at the University of Southern California's Rocket Propulsion Laboratory, in Los Angeles. Noone went on to work at SpaceX and Ellis at Blue Origin before they got back together and formed Relativity in 2015.

Both of their former companies use additive manufacturing to build some rocket components, but Noone and Ellis wanted to take the approach much further. They saw an opportunity to completely rethink how rockets are designed and manufactured. By simplifying designs and production processes, they figured, they would also simplify the mental labor, the "cognitive overhead," involved in building a rocket.

Rockets typically have a huge number of individual parts: The space-shuttle system, for example, consisted of 2.5 million moving parts. All the pieces must fit together just right and can't unexpectedly add up to an out-of-tolerance assembly. Every part must be manufactured, tested, installed, and tested again. More work ensues if a part needs to be fixed. And all these processes require engineers, technicians, tooling, and paperwork.

With additive manufacturing, you can design parts that incorporate several pieces that would traditionally be manufactured separately and assembled. Fewer parts means fewer interfaces and fewer chances for something to go wrong.

Our approach to designing and building our rocket engine is a case in point. Inside a typical rocket engine you'll find an injector that mixes the fuel with the oxidizer as they enter the combustion chamber, where an igniter starts the fire. The combustion produces hot gas, which moves through a nozzle to create thrust. It sounds simple in principle, but the reality is staggeringly complex. Consider that Rocketdyne's F-1 engine, which launched Saturn V rockets during NASA's Apollo program, contained a combustion chamber and nozzle assembly composed of more than 5,000 individually manufactured parts (and that's not including the injector).

Relativity's engine, Aeon 1, is a different story. To build the engine, we employ commercial 3D printers that use a process called direct metal laser sintering, in which a laser fuses together particles of metal powder, creating the required structure layer by layer. The simplest variant of the engine, a pressure-fed version that uses pressurized gas to push the fuel and oxidizer from their tanks into the combustion chamber, is manufactured by pressing the printer's on button three times (to print three parts). And we're going further: We expect commercial printers to become available soon that will allow us to print the injector, igniter, combustion chamber, and nozzle as a single part.

We use that pressure-fed engine for development and testing; the engine that will eventually fly will use turbopumps instead of simple pressurized gas to move the fuel (liquid methane) and oxidizer (liquid oxygen). These turbopumps, which are better suited for rockets with large fuel tanks, will increase the part count, but the manufacturing process will still be vastly simpler than any before.

Many rocket engines use a technique called regenerative cooling, in which liquid fuel is pumped through cooling channels around the combustion chamber to suck heat away. In a traditional manufacturing and assembly process, a thick piece of copper is shaped by spinning it rapidly while applying pressure to form the inner contours of the combustion chamber. It is then milled to create intricate cooling channels on the outside. A strong outer jacket is then brazed onto the copper structure, and a fuel-inlet manifold is welded onto the outer jacket. The whole engine assembly requires finish machining to hold tight tolerances where things fit together. Each of these processes is an opportunity for design or manufacturing error. The Aeon engine also uses regenerative cooling, but its combustion chamber is created in a single print. What's more, 3D printing enables us to incorporate many more tiny cooling channels than can be produced by milling the metal.

It's normally a monumental task to get a single engine designed, fabricated, and on the test stand. This process takes 10 to 12 months using traditional methods. A major redesign takes almost as long. But we're able to iterate much faster. In our initial tests of the Aeon engine, we tried out five versions within 14 months, firing the engines more than 100 times.

AS NASA ASTRONAUT Donald Pettit explained in his brilliant article "The Tyranny of the Rocket Equation," published on the NASA website, getting out of Earth's gravity well is not an easy task. Rockets are largely empty vessels waiting to be filled with fuel. Pettit explains that 94 percent of the mass of a can of soda comes from the soda, and 6 percent from the can. The space shuttle's external fuel tank was 96 percent fuel and 4 percent tank, an impressive improvement over soda-can technology when you consider that the fuel tank held cryogenic liquids that had to be pumped out at a rate of 1.5 metric tons of fuel per second.

The entire Terran 1 rocket is designed for simplicity. The tanks that hold the fuel and oxidizer are "autogenously pressurized," which means a small percentage of vaporized fuel and oxidizer is pumped back into their respective tanks to replace the volume of liquid as it drains. To continue Pettit's analogy, picture an unopened soda can, which is rigid and strong despite the thin shell of the can; once the can has been opened, though, it can be crushed with ease. Similarly, rockets use internal pressure to help create a lightweight yet strong vehicle.

These autogenous systems on Terran 1's tanks eliminate the need for the special pressure vessel that many rockets use inside their fuel and oxidizer tanks. Those pressure vessels hold inert gases such as helium at extremely high pressures until they're ready to be released into the tank to provide internal pressure. These vessels are notoriously difficult systems to engineer and manufacture and have been involved in several rocket failures in the last decade, including the explosion of a SpaceX Falcon 9 rocket in 2015.

Commercial printers that use metal laser sintering are suitable for manufacturing our engines, but they wouldn't be

BLAZING THE TRAIL: The Stargate printer [above] is the world's first 3D printer that can make massive metal objects like a rocket's fuel tank. A printer head [opposite, top] deposits metal wire and melts it into place to build up a tank, line by line [opposite, middle]. The tank connects to the engine and nozzle extension [opposite, bottom] to form the rocket's second stage.

practical for producing the tanks. Those printers work by selectively melting the desired portions of metal powder to create the solid material in each layer of a part. Because the powder bed needs to be flat and even for each layer, the entire work space of a printer must be filled with powder, regardless of how much material will actually be solidified. Most of that powder can be recycled, but some is lost on every print. Producing a tank using a laser sintering printer would require an unrealistic amount of metal powder and would be very slow.

That's why we designed and built Stargate, our enormous 3D printer of a different kind. It uses an existing technique called directed energy deposition but operates at a scale never before seen. The printer feeds a metal wire into the deposition area and uses energy (typically a powerful laser) to melt the wire, building up printed parts layer by layer.

Stargate places molten metal only where it is needed to build the structure, which significantly cuts down on wasted material. It uses three massive robotic arms, one of which terminates in the printer head that feeds out the wire; the two others hold working tools for finishing the printed component. We also wrote proprietary software to manage the "path planning" involved in turning a design into detailed instructions for the robotic arms.

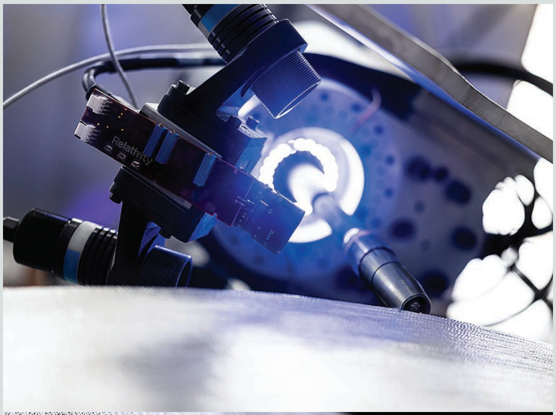
Stargate has a few limitations. Its robotic arms move its working tools through free space as it prints, which means the geometries that can be printed are constrained by the kinematics of the robotic arms—they can reach only so far and must avoid colliding with the printed structure. And as the wire melts, the bead size resulting from the welding process sets the minimum resolution of the print. But these restrictions aren't serious when it comes to large pressure vessels and structural elements.

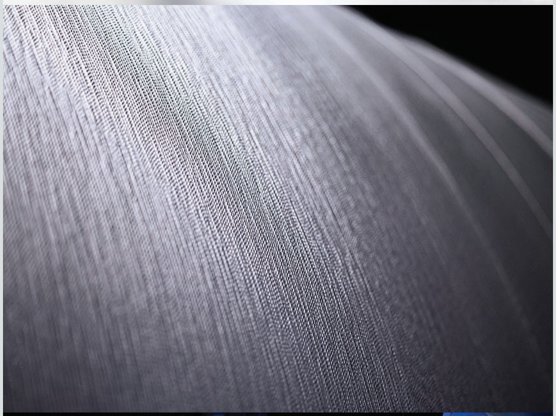
Our Stargate printer is a novel piece of technology, and we believe it opens up new frontiers in aerospace manufacturing. But the novelty of this printing process also means that we cannot rely on preexisting material data or process parameters to achieve high-quality products. Relativity has in-house metallurgists who are honing the process, ensuring that our components meet the strict quality standards for aerospace hardware.

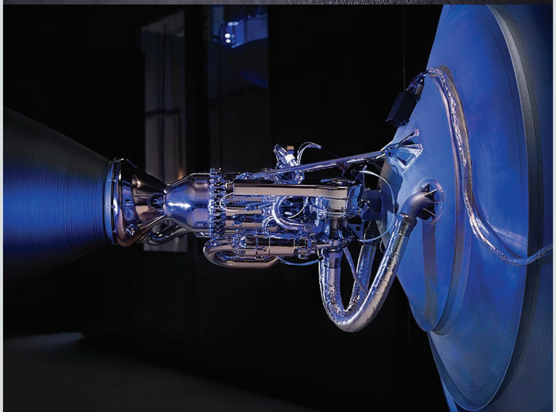
IN TRADITIONAL AEROSPACE manufacturing, a design change can require almost a year of retooling and adjustments. Because hardware changes take so long, the avionics department is usually the most agile part of an aerospace company. Avionics teams (which handle the electronics that manage the rocket's guidance, navigation, communications, and more) are accustomed to implementing last-minute software changes to fix issues on other parts of the vehicle.

The situation is completely reversed at Relativity, where the hardware team can make substantial design changes and still produce a new tank or engine within days. They can revise their plans so quickly that they challenge the avionics team's ability to produce printed circuit boards (PCBs) and construct the cable harnessing that connects all the electronics and wiring. Avionics has to adapt to an ever-changing and improving rocket.

That's why we designed the avionics of the Terran 1 rocket to be as modular as possible. We assume that sensors and actuators will be changed, and so we designed the electronics in a way that would limit the impact of such modifications. To accomplish this feat we devised a few proprietary methods of busing, minimizing the number of connectors and pins. We make every effort to reduce the amount of harnessing, which is one of the least reliable parts of the avionics on a rocket—every connection of every wire is a potential failure point. Wherever possible, we use standards such as the Controller Area Network bus protocol (for enabling communication between microcontrollers and devices) and Ethernet, and thus can use existing industry tools for testing and development. This approach means we don't waste time hunting for bugs in custom protocols and can instead focus on ensuring the proper operation of our avionics in their specific use cases.







As we consider each small design choice in the avionics systems, we aim for global rather than local optimization. For example, we use standard tools that automate electronics design, such as Altium Designer, to create basic spaceflight-qualified circuits that we can use in multiple ways throughout the rocket. We call these "bread and butter circuits," and we use them in voltage converters, processors, sensor interfaces, and other components. When our engineers tackle a new problem, they build on the work that's already been done, rather than starting from scratch. While this may sound like a commonsense approach, you'd be surprised at how many rockets contain a complicated assortment of circuit designs simply because different engineers solved the same problem in slightly different ways.

Another example can be found in our firmware. For internal communications within our avionics boxes, we don't always use a protocol that's optimized for PCBs, which would provide tiny benefits in performance and mass. Instead we sometimes use a protocol that we also use for external box-to-box communications. This method cuts the cost and time of firmware development considerably. What's more, it gives us flexibility for our design solutions: We can make changes within a centralized box, or we can add on some last-minute sensor in the harnessing, but the software doesn't know the difference. This approach may not be optimal for the avionics systems viewed in isolation, but it gives us many advantages elsewhere in regard to designing, building, and flying rockets.

Relativity CEO Ellis often reminds us that we should put at least as much thought into designing and producing our company's culture as we do into designing and building our rocket. Relativity is focused on maintaining flexibility, so experimentation is encouraged. This attitude is antithetical to the culture of traditional aerospace companies, which try to lock down their designs as soon as possible. We have an aggressive goal—to launch Terran 1 by early 2021. So we leverage our modular approach to swap out pieces, and we're constantly tweaking to optimize our designs for the world's first 3D-printed rocket.

The Terran 1, which is about 30 meters tall and 2 meters wide, is intended to launch modestly sized satellites into low Earth orbit at a cost that is radically lower than competitors can offer. It will enable smaller companies to book the whole payload of a rocket and send it to their desired orbit on their own schedule, rather than having to piggyback on the flight of a bigger rocket whose destination orbit and schedule is controlled by another company.

Relativity Space may stumble, but with our emphasis on design and manufacturing flexibility we can afford to fail many times over. We learn from every failure and forge ahead. We're watching the future of rocketry materialize before our eyes. ■

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The Carbon-Free Farm

HOMEGROWN HORSEPOWER: Farms didn't always haul in fuel and fertilizer from far away. A farm that can make both necessities on-site contributes less to climate change.

How an Iowa farm uses solar power to generate fuel and fertilizer on-site

By Jay Schmuecker

ALL PHOTOS: SCHMUECKER RENEWABLE ENERGY SYSTEM

YOU COULD SAY THAT FARMING IS in my blood: My grandparents on both sides ran large, prosperous farms in Iowa. One of my fondest childhood memories is of visiting my maternal grandparents' farm and watching the intricate moving mechanisms of the threshing machine. I guess it's not surprising that I eventually decided to study mechanical engineering at MIT. I never really considered a career in farming.

Shortly after I graduated in 1957 and took a job with the California Institute of Technology's Jet Propulsion Lab, the Soviets launched Sputnik. I was at the right place at the right time. JPL was soon transferred to the newly formed NASA. And for more than 50 years, I worked with some of the brightest engineers in the world to send unmanned spacecraft—including Mariner, Viking, and Voyager—to all the other planets in the solar system.

But my love of farms and farming never went away, and in 1999, I purchased my paternal grandfather's 130-hectare (320-acre) property, Pinehurst Farm, which had been out of the family for 55 years. I wasn't exactly sure what I'd do with the place, but by the time I retired in 2007, there was more and more talk about climate change due to human-caused carbon emissions. I knew that agriculture has a large carbon footprint, and I wondered if there was a way to make farming more sustainable. After all, the most recent numbers are alarming: The World Meteorological Organization reports that the planet is on course for a rise in temperature of 3 to 5 °C by 2100. The U.S. Environmental Protection Agency estimates that agriculture and forestry accounted for almost 10 percent of greenhouse gas emissions in 2016. While a significant share of those are livestock emissions (that is, belches and flatulence), much of it comes from burning fuel to grow, harvest, and transport food, as well as fertilizer production.

I recalled a conversation I'd had with my dad and his friend, Roy McAlister, right after I acquired the farm. Roy was the president of the American Hydrogen Association, and he owned a hydrogen-powered Nissan pickup truck. Both men were vocal advocates for replacing fossil fuels with hydrogen to reduce the United States' dependence on oil imports. The same transition would also have a big impact on carbon emissions.

And so, in 2008, I decided to create a solar-hydrogen system for Pinehurst Farm as a memorial to my father.

I'd use solar power to run the equipment that would generate fuel for a hydrogen-burning tractor. Several years into the project, I decided to also make ammonia (nitrogen trihydride, or NH_3) to use as tractor fuel and crop fertilizer.

CARBON-FREE FARMING: Creating fuel and fertilizer on the farm requires a lot of interconnected parts. Behind the solar panels, a long, squat building houses the tractor and control equipment; two small white huts house the ammonia generator and hydrogen pumps. The white tanks in front of them store the generated nitrogen and hydrogen, while the large gray tanks store additional hydrogen at high pressure. To the far right are the steps and railings of the tractor fueling dock.

My aim is to make the public—especially farmers—aware that we will need to develop such alternative fuels and fertilizers as fossil fuels become depleted and more expensive, and as climate change worsens. Developing local manufacturing processes to generate carbon-free fuel and fertilizer and powering those processes with renewable energy sources like solar and wind will eliminate farmers' reliance on fossil fuels. And doing this all locally will remove much of the cost of transporting large amounts of fuel and fertilizers as well. At our demonstration project at Pinehurst, my colleague David Toyne, an engineer based in Tujunga, Calif., and I have shown that sustainable farming is possible. But much like designing spacecraft, the effort has taken a little longer and presented many more challenges than we initially expected.

The system that we now have in place includes several main components: a retrofitted tractor that can use either hydrogen or ammonia as fuel; generators to create pure hydrogen and pure nitrogen, plus a reactor to combine the two into ammonia; tanks to store the various gases; and a grid-tied solar array to power the equipment. When I started, there were no other solar-hydrogen farms on which I could model my farm, so every aspect had to be painstakingly engineered from scratch, with plenty of revisions, mishaps, and discoveries along the way.

The work began in earnest in 2009. Before actually starting to build anything, I crunched the numbers to see what would be needed to pull off the project. I found that a 112-kilowatt (150-horsepower) tractor burns about 47 liters per hectare (5 gallons per acre) if you're raising corn and about two-thirds that amount for soybeans. The same area would require 5 kilograms of hydrogen fuel. That meant we needed roughly 1,400 kg of hydrogen to fuel the tractor and other farm vehicles from planting to harvest. Dennis Crow, who farms the Pinehurst land, told me about half the fuel would go toward spring planting and half for fall harvesting. The growing season in Iowa is about 150 days, so we'd need to make about 4.5 kg of hydrogen per day to have 700 kg of hydrogen for the harvest. Spring planting would be easier—we would have 215 days of the year to make the remaining fuel.

To generate the hydrogen, we would split water into hydrogen and oxygen. By my calculations, running the hydrogen generator and related equipment would require about 80 kW of solar power. I decided to use two-axis solar arrays, which track the sun to boost the collection capacity by 30 percent. Based on the efficiency of commodity photovoltaic panels in 2008, we'd need 30 solar arrays, with each array holding 12 solar panels.

That's a lot of solar panels to install, operate, and maintain, and a lot of hydrogen to generate and store. I soon realized I could not afford to build a complete operational system. Instead, I focused on creating a demonstration system at one-tenth scale, with three solar arrays instead of 30. While the tractor would be full size, we would make only 10 percent of the hydrogen needed to fuel it. I decided that even a limited demonstration would be a worthwhile proof of concept. Now we had to figure out how to make it happen, starting with the tractor.

AMMONIA POWER: The tractor [left] initially ran exclusively on hydrogen fuel, but it was later modified to also run on ammonia at the flick of a switch. Pressurized hydrogen and nitrogen tanks [right] stand upright inside the ammonia shed, waiting to be mixed.

As it turns out, I wasn't the first to think of using hydrogen as a tractor fuel. Back in 1959, machinery manufacturer Allis-Chalmers demonstrated a tractor powered by hydrogen fuel cells. Fifty-two years later, New Holland Agriculture did the same. Unfortunately, neither company produced a commercial model. After some further research, I decided that fuel cells were (and still are) far too expensive. Instead, I would have to buy a regular diesel tractor and convert it to run on hydrogen.

Tom Hurd, an architect in Mason City, Iowa, who specializes in renewable-energy installations, assisted with the farm's overall design. At his suggestion, I contacted the Hydrogen Engine Center in nearby Algona, Iowa. The company's specialty was modifying internal combustion engines to burn hydrogen, natural gas, or propane. Ted Hollinger, the center's president, agreed to provide a hydrogen-fueled engine for the tractor.

Hollinger's design started with a gasoline-fueled Ford 460 V-8 engine block. He suggested that we include a small propane tank as backup in case the tractor ran out of hydrogen out in the field. Several months later, though, he recommended that we use ammonia instead of propane, to avoid fossil fuels completely. Since the idea was to reduce the farm's carbon footprint, I liked the ammonia idea.

Scott McMains, who looks after the old cars that I store on the farm, located a used 7810 John Deere tractor as well as a Ford 460 engine. The work of installing the Ford engine into the tractor was done by Russ Hughes, who lives in Monticello, Iowa, and was already restoring my 1947 Buick Roadmaster sedan.

The tractor would need to carry several large, heavy fuel tanks for the hydrogen and ammonia. Bob Bamford, a retired JPL structural-design analyst, took a look at my plans for the fuel tanks' support structure and redesigned it. In my original design, the support structure was bolted together, but Bamford's design used welds for increased strength. I had the new and improved design fabricated in California.

The completed tractor was delivered to the farm in late 2014. With the flick of a switch in the cab, our tractor can toggle between burning pure hydrogen and burning a mixture of hydrogen and ammonia gas. Pure ammonia won't burn in an internal combustion engine; you first need to mix it with about 10 percent hydrogen. The energy content of a gallon of ammonia is about 35 percent that of diesel. The fuel is then mixed with the intake air and injected into the tractor's computer-controlled, spark-ignited engine cylinders. The tractor can run for 6 hours at full power before it needs to be refueled.

While work on the tractor proceeded, we were also figuring out how to generate the hydrogen and ammonia it would burn.

Ramsey Creek Woodworks of Kalona, Iowa, modified the farm's old hog shed to house the hydrogen generators, control equipment, and the tractor itself. The company also installed the solar trackers and the solar arrays.

We constructed a smaller building to house the pumps that would compress the hydrogen for high-pressure storage. Hydrogen is of course incredibly flammable. For safety, I designed low slots in the walls on two sides so that air could enter and vent out the top, taking with it any leaked hydrogen.

So how does the system actually produce hydrogen? The generator I purchased, from a Connecticut company called Proton OnSite, creates hydrogen and oxygen by splitting water that we pipe in from an on-site well. It is rated to make 90 grams (3 ounces) of hydrogen per hour. With the amount of sunlight Iowa receives, I can make an average of 450 grams of hydrogen per day. We can

PUTTING IT TOGETHER: From left, Ted Hollinger, David Toyne, Jay Schmuecker, and Tom Hurd stand in front of the tractor [far left]. The modified tractor engine [center left] features hydrogen injectors, which are the small black caps located directly below the long silver bar, and liquid ammonia injectors, which are contained in the silver cylinder on top of the engine. The nitrogen generator [center right] is key to reducing the amount of oxygen in the air mixture and making the nitrogen pure enough to be used for fuel. Toyne sits next to the panel [far right] that controls the hydrogen and nitrogen generators, air compressors, and other equipment.

make more on a summer day, when we have more daylight, than we can in winter.

The generator was designed to operate continuously. But we'd be relying on solar power, which is intermittent, so David Toyne, who specializes in factory automation and customized systems, worked with Proton to modify it. Now the generator makes less hydrogen on overcast days and enters standby when the solar arrays' output is too low. At the end of each day, the generator automatically turns off after being on standby for 20 minutes.

Generating ammonia posed some other challenges. I wanted to make the ammonia on-site, so that I could show it was possible for a farm to produce its fuel and fertilizer with no carbon emissions.

A substantial percentage of the world's population depends on food grown using nitrogen-based fertilizers, including ammonia. It's hard to beat for boosting crop yields. For example, Adam Sylvester, Pinehurst's farm manager, told me that if we did not use nitrogen-based fertilizers on our cornfields, the yield would be about 250 bushels per hectare (100 bushels per acre), instead of the 500 bushels we get now. Clearly, the advantages to producing ammonia on location extend beyond just fuel.

But ammonia production also accounts for about 1 percent of all greenhouse emissions, largely from the fossil fuels powering most reactors. And just like hydrogen, ammonia comes with safety concerns. Ammonia is an irritant to the eyes, respiratory tract, mucus membranes, and skin.

Even so, ammonia has been used for years in refrigeration as well as fertilizer. It's also an attractive carbon-free fuel. A ruptured ammonia tank won't explode or catch fire as a propane tank will, and the liquid is stored at a much lower pressure than is hydrogen gas (1 megapascal for ammonia versus 70 MPa for hydrogen).

While attending the NH3 Fuel Conference in Sacramento in 2013, I had dinner with Bill Ayres, a director for the NH3 Fuel Association, and we discussed my interest in making ammonia in a self-contained system. Ayres pointed me to Doug Carpenter, who had developed a way to make ammonia on a small scale—provided you already have the hydrogen. Which I did. Carpenter delivered the reactor in 2016, several months before his untimely passing.

We turned again to Ramsey Creek to construct the ammonia-generation building. The 9-square-meter building, similar in design to the hydrogen shed, houses the pumps, valves, controls, ammonia reactor, collector tanks, and 10 high-pressure storage tanks. We make nitrogen by flowing compressed air through a nitrogen generator and removing the atmospheric oxygen. Before entering the reactor, the hydrogen and nitrogen are compressed to 24 MPa (3,500 pounds per square inch).

It's been a process of trial and error to get the system right. When we first started making ammonia, we found it took too long for the reactor's preheater to heat the hydrogen and nitrogen, so we added electrical band heaters around the outside of the unit. Unfortunately, the additional heat weakened the outer steel shell, and the next time we attempted to make ammonia, the outer shell split open. The mixed gases, which were under pressure at 24 MPa, caught fire. Toyne was in the equipment room at the time and noticed

the pressure dropping. He made it out to the ammonia building in time to take pictures of the flames. After a few minutes, the gas had all vented through the top of the building. Luckily, only the reactor was damaged, and no one was hurt.

After that incident, we redesigned the ammonia reactor to add internal electrical heaters, which warm the apparatus before the gases are introduced. We also insulated the outer pressure shell from the heated inside components. Once started, the reaction forming the ammonia needs no additional heat.

Our ammonia system, like our hydrogen and nitrogen systems, is hooked up to the solar panels, so we cannot run it round the clock. Also, because of the limited amount of solar power we have, we can make either hydrogen or nitrogen on any given day. Once we have enough of both, we can produce a batch of ammonia. At first, we had difficulty producing nitrogen pure enough for ammonia production, but we solved that problem by mixing in a bit of hydrogen. The hydrogen bonds with the oxygen to create water vapor, which is far easier to remove than atmospheric oxygen.

We've estimated that our system uses a total of 14 kilowatt-hours to make a liter of ammonia, which contains 3.8 kWh of energy. This may seem inefficient, but it's comparable to the amount of usable energy we could get from a diesel-powered tractor. About two-thirds of the electrical energy is used to make the hydrogen, one-quarter is used to make the nitrogen, and the remainder is for the ammonia.

Each batch of ammonia is about 38 liters (10 gallons). It takes 10 batches to make enough ammonia to fertilize 1.2 hectares of the farm's nearly 61 hectares (3 of 150 acres) of corn. Thankfully, we can use the same ammonia for either application—it has to be liquid regardless of whether we're using it for fertilizer or fuel.

We now have the basis of an on-site carbon-emission-free system for fueling a tractor and generating fertilizer, but there's still plenty to improve. The solar arrays were sized to generate only hydrogen. We need additional solar panels or perhaps wind turbines to make more hydrogen, nitrogen, and ammonia. In order to make these improvements, we've created the Schmuecker Renewable Energy System, a nonprofit organization that accepts donations.

Toyne compares our system to the Wright brothers' airplane: It is the initial demonstration of what is possible. Hydrogen and ammonia fuels will become more viable as the equipment costs decrease and more people gain experience working with them. I've spent more than US $2 million of my retirement savings on the effort. But much of the expense was due to the custom nature of the work: We estimate that to replicate the farm's current setup would cost a third to half as much and would be more efficient with today's improved equipment.

We've gotten a lot of interest about what we've installed so far. Our tractor has drawn attention from other farmers in Iowa. We've received inquiries from Europe, South Africa, Saudi Arabia, and Australia about making ammonia with no carbon emissions. In May 2018, we were showing our system to two employees of the U.S. Department of Energy, and they were so intrigued they invited us to present at an Advanced Research Projects Agency–Energy (ARPA-E) program on renewable, carbon-free energy generation that July.

Humankind needs to develop renewable, carbon-emission-free systems like the one we've demonstrated. If we do not harness other energy sources to address climate change and replace fossil fuels, future farmers will find it harder and harder to feed everyone. Our warming world will become one in which famine is an everyday occurrence. ■

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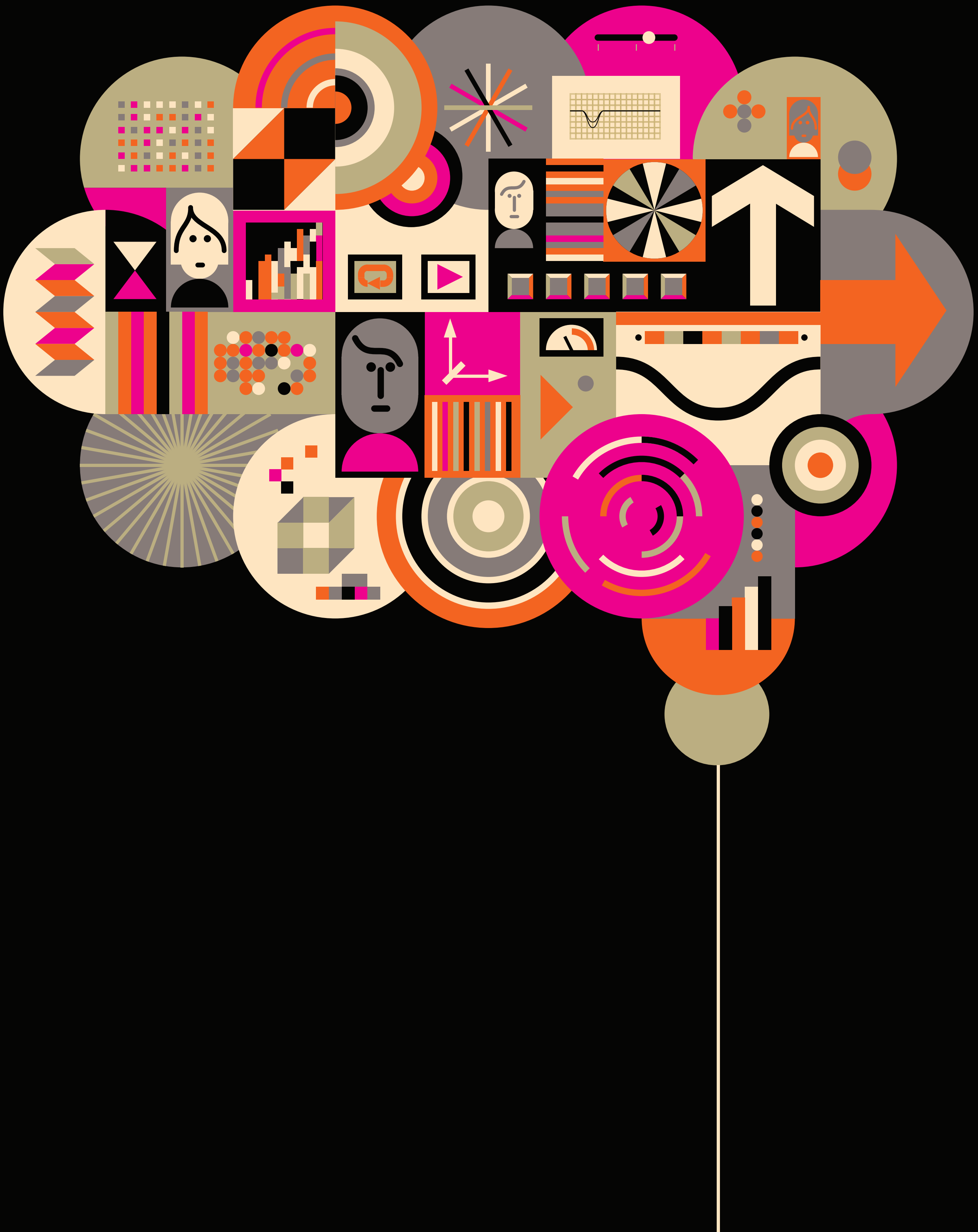


A Man-Machine Mind Meld for Quantum Computing

CAN AN ONLINE GAME THAT COMBINES HUMAN BRAINPOWER WITH AI SOLVE INTRACTABLE PROBLEMS?

BY OTTÓ ELÍASSON, CARRIE WEIDNER, JANET RAFNER & SHAEEMA ZAMAN AHMED

ILLUSTRATION BY Greg Mably

ANYONE OF A CERTAIN AGE who has even a passing interest in computers will remember the remarkable breakthrough that IBM made in 1997 when its Deep Blue chess-playing computer defeated Garry Kasparov, then the world chess champion. Computer scientists passed another such milestone in March 2016, when DeepMind (a subsidiary of Alphabet, Google's parent company) announced that its AlphaGo program had defeated world-champion player Lee Sedol in the game of Go, a board game that had vexed AI researchers for decades. Recently, DeepMind's algorithms have also bested human players in the computer games *StarCraft II* and *Quake Arena III*. ¶ Some believe that the cognitive capacities of machines will overtake those of human beings in many spheres within a few decades. Others are more cautious and point out that our inability to understand the source of our own cognitive powers presents a daunting hurdle. How can we make thinking machines if we don't fully understand our own thought processes?

Citizen science, which enlists masses of people to tackle research problems, holds promise here, in no small part because it can be used effectively to explore the boundary between human and artificial intelligence.

Some citizen-science projects ask the public to collect data from their surroundings (as eButterfly does for butterflies) or to monitor delicate ecosystems (as Eye on the Reef does for Australia's Great Barrier Reef). Other projects rely on online platforms on which people help to categorize obscure phenomena in the night sky (Zooniverse) or add to the understanding of the structure of proteins (Foldit). Typically, people can contribute to such projects without any prior knowledge of the subject. Their fundamental cognitive skills, like the ability to quickly recognize patterns, are sufficient.

In order to design and develop video games that can allow citizen scientists to tackle scientific problems in a variety of fields, professor and group leader Jacob Sherson founded ScienceAtHome (SAH), at Aarhus University, in Denmark. The group began by considering topics in quantum physics, but today SAH hosts games covering other areas of physics, math, psychology, cognitive science, and behavioral economics. We at SAH search for innovative solutions to real research challenges while providing insight into how people think, both alone and when working in groups.

We believe that the design of new AI algorithms would benefit greatly from a better understanding of how people solve problems. This surmise has led us to establish the Center for Hybrid Intelligence within SAH, which tries to combine human and artificial intelligence, taking advantage of the particular strengths of each. The center's focus is on the gamification of scientific research problems and the develop-

ment of interfaces that allow people to understand and work together with AI.

OUR FIRST GAME, *Quantum Moves*, was inspired by our group's research into quantum computers. Such computers can in principle solve certain problems that would take a classical computer billions of years. Quantum computers could challenge current cryptographic protocols, aid in the design of new materials, and give insight into natural processes that require an exact solution of the equations of quantum mechanics—something normal computers are inherently bad at doing.

One candidate system for building such a computer would capture individual atoms by "freezing" them, as it were, in the interference pattern produced when a laser beam is reflected back on itself. The captured atoms can thus be organized like eggs in a carton, forming a periodic crystal of atoms and light. Using these atoms to perform quantum calculations requires that we use tightly focused laser beams, called optical tweezers, to transport the atoms from site to site in the light crystal. This is a tricky business because individual atoms do not behave like particles; instead, they resemble a wavelike liquid governed by the laws of quantum mechanics.

In *Quantum Moves*, a player manipulates a touch screen or mouse to move a simulated laser tweezer and pick up a trapped atom, represented by a liquidlike substance in a bowl. Then the player must bring the atom back to the tweezer's initial position while trying to minimize the sloshing of the liquid. Such sloshing would increase the energy of the atom and ultimately introduce errors into the operations of the quantum computer. Therefore, at the end of a move, the liquid should be at a complete standstill.

To understand how people and computers might approach such a task differently, you need to know something about how computerized optimization algorithms work. The countless ways of moving a glass of water without spilling may be regarded as constituting a "solution landscape." One solution is represented by a single point in that landscape, and the height of that point represents the quality of the solution—how smoothly and quickly the glass of water was moved. This landscape might resemble a mountain range, where the top of each mountain represents a local optimum and where the challenge is to find the highest peak in the range—the global optimum.

Researchers must compromise between searching the landscape for taller mountains ("exploration") and climbing to the top of the nearest mountain ("exploitation"). Making such a trade-off may seem easy when exploring an actual physical landscape: Merely hike around a bit to get at least the general lay of the land before surveying in greater detail what seems to be the tallest peak. But because each possible way of changing the solution defines a new dimension, a realistic problem can have thousands of dimensions. It is computationally intractable to completely map out such a higher-dimensional landscape. We call this the curse of high dimensionality, and it plagues many optimization problems.

Although algorithms are wonderfully efficient at crawling to the top of a given mountain, finding good ways of searching through the broader landscape poses quite a challenge, one that is at the forefront of AI research into such control problems. The conventional approach is to come up with clever ways of reducing the search space, either through insights generated by researchers or with machine-learning algorithms trained on large data sets.

ILLUSTRATION BY Greg Mably

At SAH, we attacked certain quantum-optimization problems by turning them into a game. Our goal was not to show that people can beat computers in this arena but rather to understand the process of generating insights into such problems. We addressed two core questions: whether allowing players to explore the infinite space of possibilities will help them find good solutions and whether we can learn something by studying their behavior.

Today, more than 250,000 people have played *Quantum Moves*, and to our surprise, they did in fact search the space of possible moves differently from the algorithm we had put to the task. Specifically, we found that although players could not solve the optimization problem on their own, they were good at searching the broad landscape. The computer algorithms could then take those rough ideas and refine them.

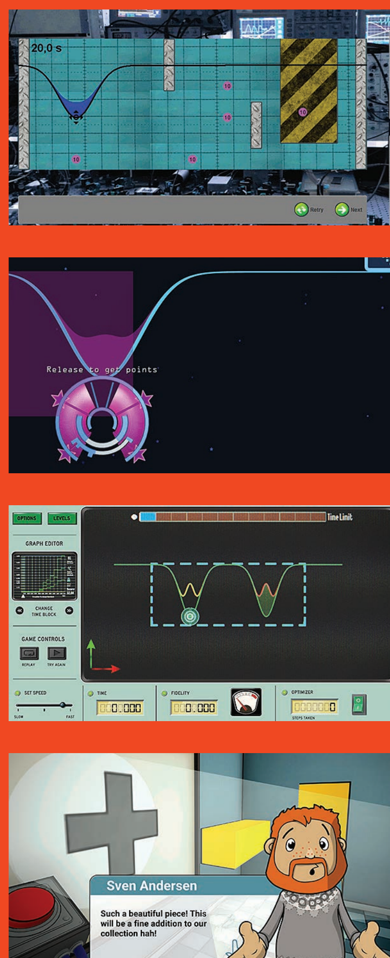
Perhaps even more interesting was our discovery that players had two distinct ways of solving the problem, each with a clear physical interpretation. One set of players started by placing the tweezer close to the atom while keeping a barrier between the atom trap and the tweezer. In classical physics, a barrier is an impenetrable obstacle, but because the atom liquid is a quantum-mechanical object, it can tunnel through the barrier into the tweezer, after which the player simply moved the tweezer to the target area. Another set of players moved the tweezer directly into the atom trap, picked up the atom liquid, and brought it back. We called these two strategies the "tunneling" and "shoveling" strategies, respectively.

Such clear strategies are extremely valuable because they are very difficult to obtain directly from an optimization algorithm. Involving humans in the optimization loop can thus help us gain insight into the underlying physical phenomena that are at play, knowledge that may then be transferred to other types of problems.

Quantum Moves raised several obvious issues. First, because generating an exceptional solution required further computer-based optimization, players were unable to get immediate feedback to help them improve their scores, and this often left them feeling frustrated. Second, we had tested this approach on only one scientific challenge with a clear classical analogue, that of the sloshing liquid. We wanted to know whether such gamification could be applied more generally, to a variety of scientific challenges that do not offer such immediately applicable visual analogies.

We address these two concerns in *Quantum Moves 2*. Here, the player first generates a number of candidate solutions by playing the original game. Then the player chooses which solutions to optimize using a built-in algorithm. As the algorithm improves a player's solution, it modifies the solution path—the movement of the tweezer—to represent the optimized solution. Guided by this feedback, players can then improve their strategy, come up with a new solution, and iteratively feed it back into this process. This gameplay provides high-level heuristics and adds human intuition to the algorithm. The person and the machine work in tandem—a step toward true hybrid intelligence.

In parallel with the development of *Quantum Moves 2*, we also studied how people collaboratively solve complex problems. To that end, we opened our atomic physics laboratory to the general public—virtually. We let people from around the world dictate the experiments we would run to see if they would find ways to improve the results we were getting. What results? That's a little tricky to explain, so we need to pause for a moment and provide a little background on the relevant physics.



FUN AND GAMES: The *Quantum Moves* game evolved over time, from a relatively crude early version [top] to its current form [second from top] and then a major revision, *Quantum Moves 2* [third from top]. *Skill Lab: Science Detective* games [bottom] test players' cognitive skills.

SCIENCEATHOME

One of the essential steps in building the quantum computer along the lines described above is to create the coldest state of matter in the universe, known as a Bose-Einstein condensate. Here millions of atoms oscillate in synchrony to form a wavelike substance, one of the largest purely quantum phenomena known. To create this ultracool state of matter, researchers typically use a combination of laser light and magnetic fields. There is no familiar physical analogy between such a strange state of matter and the phenomena of everyday life.

The result we were seeking in our lab was to create as much of this enigmatic substance as was possible given the equipment available. The sequence of steps to accomplish that was unknown. We hoped that gamification could help to solve this problem, even though it had no classical analogy to present to game players.

In October 2016, we released a game that, for two weeks, guided how we created Bose-Einstein condensates in our laboratory. By manipulating simple curves in the game interface, players generated experimental sequences for us to use in producing these condensates—and they did so without needing to know anything about the underlying physics. A player would generate such a solution, and a few minutes later we would run the sequence in our laboratory. The number of ultracold atoms in the resulting Bose-Einstein condensate was measured and fed back to the player as a score. Players could then decide either to try to improve their previous solution or to copy and modify other players' solutions. About 600 people from all over the world participated, submitting 7,577 solutions in total. Many of them yielded bigger condensates than we had previously produced in the lab.

So this exercise succeeded in achieving our primary goal, but it also allowed us to learn something about human behavior. We learned, for example, that players behave differently based on where they sit on the leaderboard. High-performing players make small changes to their successful solutions (exploitation), while poorly performing players are willing to make more dramatic changes (exploration). As a collective, the players nicely balance exploration and exploitation. How they do so provides valuable inspiration to researchers trying to understand human problem solving in social science as well as to those designing new AI algorithms.

HOW COULD MERE amateurs outperform experienced experimental physicists? The players certainly weren't better at physics than the experts—but they could do better because of the way in which the problem was posed. By turning the research challenge into a game, we gave players the chance to explore solutions that had previously required complex programming to study. Indeed, even expert experimentalists improved their solutions dramatically by using this interface.

Insight into why that's possible can probably be found in the words of the late economics Nobel laureate Herbert A. Simon: "Solving a problem simply means representing it so as to make the solution transparent." Apparently, that's what our games can do with their novel user interfaces. We believe that such interfaces might be a key to using human creativity to solve other complex research problems.

Eventually, we'd like to get a better understanding of why this kind of gamification works as well as it does. A first step would be to collect more data on what the players do while they are playing. But even with massive amounts of data, detecting the subtle patterns underlying human intuition is an overwhelming challenge. To advance, we need a deeper insight into the cognition of the individual players.

As a step forward toward this goal, ScienceAtHome created *Skill Lab: Science Detective*, a suite of minigames exploring visuospatial reasoning, response inhibition, reaction times, and other basic cognitive skills. Then we compare players' performance in the games with how well these same people did on established psychological tests of those abilities. The point is to allow players to assess their own cognitive strengths and weaknesses while donating their data for further public research.

In the fall of 2018 we launched a prototype of this large-scale profiling in collaboration with the Danish Broadcasting Corp. Since then more than 20,000 people have participated, and in part because of the publicity granted by the public-service channel, participation has been very evenly distributed across ages and by gender. Such broad appeal is rare in social science, where the test population is typically drawn from a very narrow demographic, such as college students.

Never before has such a large academic experiment in human cognition been conducted. We expect to gain new insights into many things, among them how combinations of cognitive abilities sharpen or decline with age, what characteristics may be used to prescreen for mental illnesses, and how to optimize the building of teams in our work lives.

And so what started as a fun exercise in the weird world of quantum mechanics has now become an exercise in understanding the nuances of what makes us human. While we still seek to understand atoms, we can now aspire to understand people's minds as well. ■

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By Efraín O’Neill-Carrillo and Agustín Irizarry-Rivera

HOW TO HARDEN PUERTO RICO’S GRID AGAINST HURRICANES

Another devastating hurricane season winds down in the Caribbean. As in previous years, we are left with haunting images of entire neighborhoods flattened, flooded streets, and ruined communities. This time it was the Bahamas, where damage was estimated at US $7 billion and at least 50 people were confirmed dead, with the possibility of many more fatalities yet to be discovered. • A little over two years ago, even greater devastation was wreaked upon Puerto Rico. The back-to-back calamity of Hurricanes Irma and Maria killed nearly 3,000 people and triggered the longest blackout in U.S. history. All 1.5 million customers of the Puerto Rico Electric Power Authority lost power. Thanks to heroic efforts by emergency utility crews, about 95 percent of customers had their service restored after about 6 months. But the remaining 5 percent—representing some 250,000 people—had to wait nearly a year. →

RESILIENCE: The yearlong blackout following Hurricane Maria underscored the fragility of Puerto Rico's power grid. Since then, installations of rooftop solar [top] combined with battery storage [bottom] have soared. A homeowner [middle] uses his smartphone to monitor how much power his solar system is generating and how much electricity his household is consuming.

Community microgrids, rooftop PV, and battery storage would help the island weather the next big storm

FROM TOP: DENNIS M. RIVERA PICHARDO/AP (2); GDA/AP

After the hurricanes, many observers were stunned by the ravages to Puerto Rico's centralized power grid: Twenty-five percent of the island's electric transmission towers were severely damaged, as were 40 percent of the 334 substations. Power lines all over the island were downed, including the critical north-south transmission lines that cross the island's mountainous interior and move electricity generated by large power plants on Puerto Rico's south shore to the more populated north.

In the weeks and months following the hurricane, many of the 3.3 million inhabitants of Puerto Rico, who are all U.S. citizens, were forced to rely on noisy, noxious diesel- or gasoline-fired generators. The generators were expensive to operate, and people had to wait in long lines just to get enough fuel to last a few hours. Government emergency services were slow to reach people, and many residents found assistance instead from within their own communities, from family and friends.

The two of us weren't surprised that the hurricane caused such intense and long-lasting havoc. For more than 20 years, our group at the University of Puerto Rico Mayagüez has studied Puerto Rico's vulnerable electricity network and considered alternatives that would better serve the island's communities.

Hurricanes are a fact of life in the Caribbean. Preparing for natural disaster is what any responsible government should do. And yet, even before the storm, we had become increasingly concerned at how the Puerto Rico Electric Power Authority, or PREPA, had bowed to partisan politics and allowed the island's electrical infrastructure to fall into disrepair. Worse, PREPA, a once well-regarded public power company, chose not to invest in new technology and organizational innovations that would have made the grid more durable, efficient, and sustainable.

In our research, we've tried to answer such questions as these: What would it take to make the island's electricity network more resilient in the face of a natural disaster? Would a more decentralized system provide better service than the single central grid and large fossil-fuel power plants that Puerto Rico now relies on? Hurricane Maria turned our academic questions into a huge, open-air experiment that included millions of unwilling subjects—ourselves included. [For more on our experiences during the storm, see Back Story, p. 2.]

As Puerto Rico rebuilds, there is an extraordinary opportunity to rethink the island's power grid and move toward a flexible, robust system capable of withstanding punishing storms. Based on our years of study and analysis, we have devised a comprehensive plan for such a grid, one that would be much better suited to the conditions and risks faced by island populations. This grid would rely heavily on microgrids, distributed solar photovoltaics, and battery storage to give utilities and residents much greater resilience than could ever be achieved with a conventional grid. We are confident our ideas could benefit island communities in any part of the world marked by powerful storms and other unpredictable threats.

As is typical throughout the world, Puerto Rico designed its electricity infrastructure around large power plants that feed into an interconnected network of high-voltage transmission lines and lower-voltage distribution lines. When this system was built, large-scale energy storage was very limited. So then, as now, the grid's control systems had to constantly match generation with demand at all times while maintaining a desired voltage and frequency across the network. About 70 percent of Puerto Rico's fossil-fuel generation is located along the island's south coast, while 70 percent of the demand is concentrated in the north, which necessitated building transmission lines across the tropical mountainous interior.

> Hurricane Maria turned our academic questions into a huge experiment that included millions of unwilling subjects—ourselves included.

The hurricane vividly exposed the system's vulnerability. Officials finally acknowledged that it made no sense for a heavily populated island sitting squarely in the Caribbean's hurricane zone to rely on a centralized infrastructure that was developed for continent-wide systems, and based on technology, assumptions, and economics from the last century. After Maria, many electricity experts called for Puerto Rico to move toward a more decentralized grid.

It was a bittersweet moment for us, because we'd been saying the same thing for more than a decade. Back in 2008, for instance, our group at the university assessed the potential for renewable energy on the island. We looked at biomass, microhydropower, ocean, photovoltaics (PV), solar thermal, wind, and fuel cells. Of these, rooftop PV stood out. We estimated that equipping about two-thirds of residential roofs with photovoltaics would be enough to meet the total daytime peak demand—about 3 gigawatts—for the entire island.

To be sure, interconnecting so much distributed energy generation to the power grid would be an enormous challenge, as we stated in the report. However, in the 11 years since that study, PV technology—as well as energy storage, PV inverters, and control software—has gotten much better and less costly. Now, more than ever, distributed-solar PV is the way to go for Puerto Rico.

Sadly, though, renewable energy did not take off in Puerto Rico. Right before Maria, renewable sources were supplying just 2.4 percent of the island's electricity, from a combination of rooftop PV, several onshore wind and solar-power farms, and a few small outdated hydropower plants.

Progress has been hamstrung by PREPA. The utility was founded as a government corporation in 1941 to interconnect the existing isolated electric systems and achieve islandwide electrification at a reasonable cost. By the early 1970s, it had succeeded.

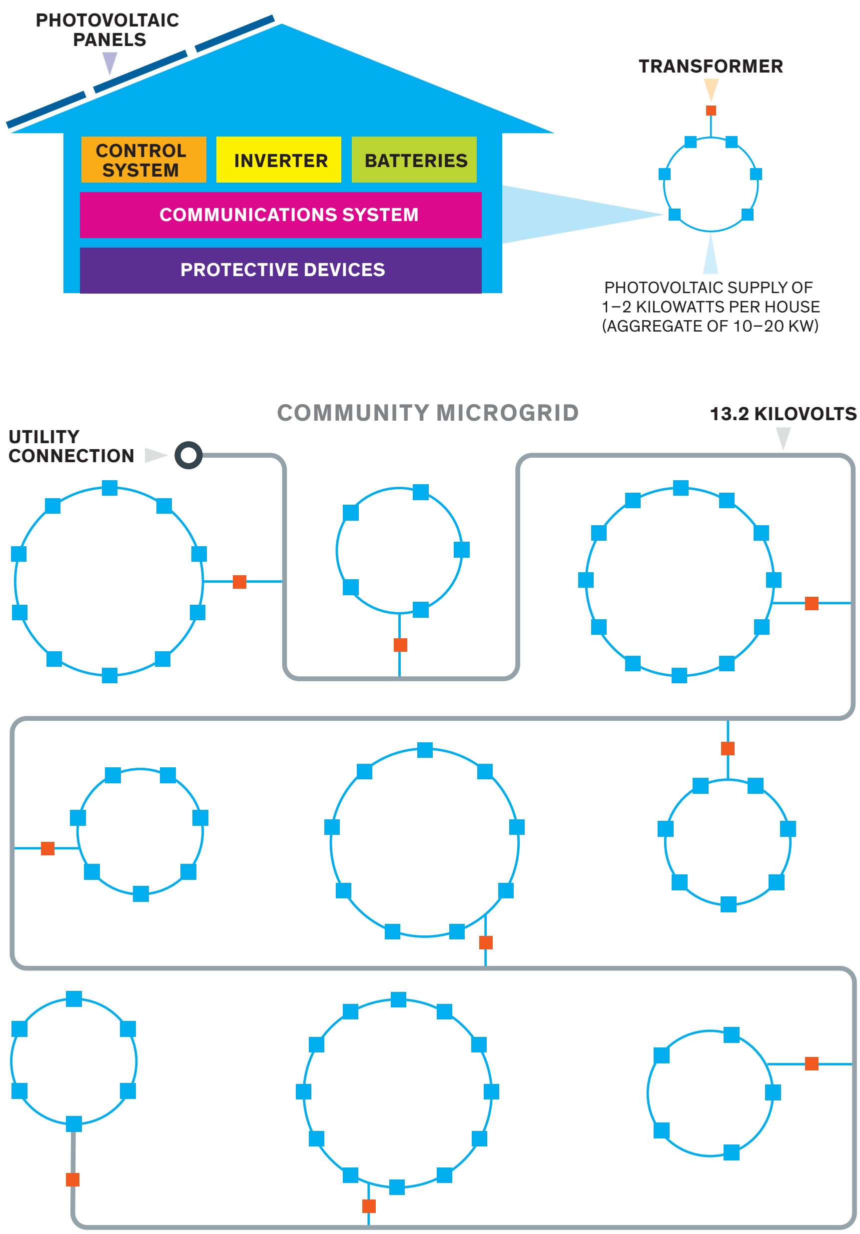
Meanwhile, generous tax incentives had induced many large companies to locate their factories and other facilities in Puerto Rico. The utility relied heavily on those large customers, which paid on time and helped finance PREPA's infrastructure improvements. But in the late

1990s, a change in U.S. tax code led to the departure of nearly 60 percent of PREPA's industrial clients. To close the gap between its revenues and operating costs, PREPA periodically issued new municipal bonds. It wasn't enough. The utility's operating and management practices failed to adapt to the new reality of more environmental controls, the rise of renewable energy, and demands for better customer service. Having accumulated $9 billion in debt, PREPA filed for bankruptcy in July 2017.

Then the hurricane struck. After the debris was cleared came the recognition—finally—that the technological options for supplying electricity have multiplied. For starters, distributed energy resources like rooftop PV and battery storage are now economically competitive with grid power in Puerto Rico. Over the last 10 years, the residential retail price of electricity has fluctuated between 20 and 27 U.S. cents per kilowatt-hour; for comparison, the average price in the rest of the United States is about 13 cents per kWh. When you factor in the additional rate increases that will be needed to service PREPA's debt, the price will eventually exceed 30 cents per kWh. That's more than the levelized cost of electricity (LCOE) from a rooftop PV system plus battery storage, at 24 to 29 cents per kWh, depending on financing and battery type. And if these solar-plus-storage systems were purchased in bulk, the LCOE would be even less.

Also, the technology now exists to match supply and demand locally, by using energy storage and by selectively lowering demand through improved efficiency, conservation, and demand-response actions. We have new control and communications systems that allow these distributed energy resources to be interconnected into a community network capable of meeting the electricity needs of a village or neighborhood.

Such a system is called a community microgrid. It is basically a small electrical network that connects electricity consumers—for example, dozens or hundreds of homes—with one or more sources of electricity, such as solar panels, along with inverters, control electronics, and some energy storage. In the event of an



A Grid of Microgrids

Hurricanes are a fact of life in the Caribbean. Installing community microgrids throughout Puerto Rico would greatly improve the island's ability to recover from severe storms and other natural disasters. In this model, groups of homes and small businesses would share rooftop solar power and battery storage. In the event of an outage on the central grid, the entire microgrid would operate in "islanded" mode. Each household would have enough power to operate essential loads, such as a small refrigerator, personal electronics, lights, and fans. Community members would be trained to operate and maintain the microgrid.

Keeping the Lights On

Staff, students, and faculty from the University of Puerto Rico Mayagüez, with support from IEEE-EPICS, built five PV kiosks in rural communities that were among the last to be reconnected to the grid after Hurricane Maria. Each kiosk provided lights, a small refrigerator for storing medicine and other perishables, and charging ports for cellphones and other electronics.

LEFT: EFRAÍN O'NEILL-CARRILLO; RIGHT: BORINTEK-JAYUYA

outage, disconnect switches enable this small grid to be quickly isolated from the larger grid that surrounds it or from neighboring microgrids, as the case may be.

Here's how Puerto Rico's grid could be refashioned from the bottom up. In each community microgrid, users would collectively install enough solar panels to satisfy local demand. These distributed resources and the related loads would be connected to one another and also tied to the main grid.

Over time, community microgrids could interconnect to form a regional grid. Eventually, Puerto Rico's single centralized power grid could even be replaced by interconnecting regional grids and community microgrids. If a storm or some other calamity threatens one or more microgrids, neighboring ones could disconnect and operate independently. Studies of how grids are affected by storms have repeatedly shown that a large percentage of power outages are caused by relatively tiny areas of grid damage. So the ability to quickly isolate the areas of damage, as a system of microgrids is able to do, can be enormously beneficial in coping with storms. The upshot is that an interconnection of microgrids would be far more resilient and reliable than Puerto Rico's current grid and also more sustainable and economical.

Could such a model actually work in Puerto Rico? It certainly could. Starting in 2009, our research group developed a model for a microgrid that would serve a typical community in Puerto Rico. In the latest version, the overall microgrid serves 700 houses, divided into 70 groups of 10 houses. Each of these groups is connected to its own distribution transformer, which serves as the connection point to the rest of the community microgrid. All of the transformers are connected by 4.16-kilovolt lines in a radial network. [See diagram, "A Grid of Microgrids."]

Rooftop PV and battery storage are now economically competitive with grid power in Puerto Rico.

Each group within the community microgrid would be equipped with solar panels, inverters, batteries, control and communications systems, and protective devices. For the 10 homes in each group, there would be an aggregate PV supply of 10 to 20 kW, or 1 to 2 kW per house. The aggregate battery storage per group is 128 kWh, which is enough to get the homes through most nights without requiring power from the larger grid. (The amounts of storage and supply in our model are based on measurements of energy demand and variations in solar irradiance in an actual Puerto Rican town; obviously, they could be scaled up or down, according to local needs.)

In our tests, we assume that each community microgrid remains connected to the central grid (or rather, a new and improved version of Puerto Rico's central grid) under normal conditions but also manages its own energy resources. We also assume that individual households and businesses have taken significant steps to improve their energy conservation and efficiency—through the use of higher-efficiency appliances, for instance. Electricity demand must still be balanced with generation, but that balancing is made easier due to the presence of battery storage.

That capability means the microgrids in our model can make use of demand response, a technique that enables customers to cut their electricity consumption by a predefined amount during times of peak usage or crisis. In exchange for cutting demand, the customer receives preferential rates, and the central grid benefits by limiting its peak demand. Many utilities around the world now use some form of demand response to reduce their reliance on fast-starting generating facilities, typically fired by natural gas, that provide additional capacity at times of peak demand. PREPA's antiquated grid, however, isn't yet set up for demand response.

During any disruption that knocks out all or part of the central grid, our model's community microgrids would disconnect from the main grid. In this "islanded" mode, the local community would continue to receive electricity from the batteries and solar panels for essential loads, such as refrigeration. Like demand response, this capability would be built into and managed by the communications and control systems. Such technology exists, but not yet in Puerto Rico.

Besides the modeling and simulation, our research group has been working with several communities in Puerto Rico that are interested in developing local microgrids and distributed-energy resources. We have helped one community secure funding to install ten 2-kW rooftop PV systems, which they eventually hope to connect into a community microgrid based on our design.

Other communities in central Puerto Rico have installed similar systems since the hurricane. The largest of these consists of 28 small PV systems in Toro Negro, a town in the municipality of Ciales. Most are rooftop PV systems serving a single household, but a few serve two or three houses, which share the resources.

Another project at the University of Puerto Rico Mayagüez built five standalone PV kiosks, which were deployed in rural locations that had no electricity for months after Maria. University staff, students, and faculty all contributed to this effort. The kiosks address the simple fact that rural and otherwise isolated communities are usually the last to be reconnected to the power grid after blackouts caused by natural disasters.

Taking this idea one step further, a member of our group, Marcel J. Castro-Sitiriche, recently proposed that the 200,000 households that were the last to be reconnected to the grid following the hurricane should receive rooftop PV and battery storage systems, to be paid for out of grid-reconstruction funds. If those households had had such systems and thus been able to weather the storm with no interruption in service, the blackout would have lasted for 6 months instead of a year. The cost of materials and installation for a 2-kW PV system with 10 kWh of batteries comes to about $7,000, assuming $3 per watt for the PV systems and $100/kWh for lead-acid batteries. Many households and small businesses spent nearly that much on diesel fuel to power generators during the months they had no grid connection.

To outfit all 200,000 of those households would come to $1.4 billion, a sizable sum. But it's just a fraction of what the Puerto Rico government has proposed spending on an enhanced central grid.

Rather than merely rebuilding PREPA's grid, Castro-Sitiriche argues, the government should focus its attention on protecting those most vulnerable to any future natural disaster.

As engineers, we're of course interested in the details of distributed-energy resources and microgrid technology. But our fieldwork has taught us the importance of considering the social implications and the end users.

One big advantage of the distributed-microgrid approach is that it's centered on Puerto Rico's most reliable social structures: families, friends, and local community. When all else failed after Hurricane Maria, those were the networks that rose to the many challenges Puerto Ricans faced. We think it makes sense to build a resilient electricity grid around this key resource. With proper training, local residents and businesspeople could learn to operate and maintain their community microgrid.

A move toward community microgrids would be more than a technical solution—it would be a socioeconomic development strategy. That's because a greater reliance on distributed energy would favor small and medium-size businesses, which tend to invest in their communities, pay taxes locally, and generate jobs.

There is a precedent for this model: Over 200 communities in Puerto Rico extract and treat their own potable water, through arrangements known as *acueductos comunitarios*, or community aqueducts. A key component to this arrangement is having a solid governance agreement among community members. Our social-science colleagues at the university have studied how community aqueducts are managed, and from them we have learned some best practices that have influenced the design of our community microgrid concept. Perhaps most important is that the community agrees to manage electricity demand in a flexible way. This can help minimize the amount of battery storage needed and therefore the overall cost of the microgrid.

During outages and emergencies, for instance, when the microgrid is running in islanded mode, users would be expected to be conservative and flexible about their electricity usage. They might have to agree to run their washing machines only on sunny days. For less conscientious users, sensors monitoring their energy usage could trigger a signal to their cellphones, reminding them to curtail their consumption. That strategy has already been successfully implemented as part of demand-response programs elsewhere in the world.

Readers living in the mainland United States or Western Europe, accustomed to reliable, round-the-clock electricity, might consider such measures highly inconvenient. But the residents of Puerto Rico, we believe, would be more accepting. Overnight, we went from being a fully electrified, modern society to having no electricity at all. The memory is still raw. A community microgrid that compels people to occasionally cut their electricity consumption and to take greater responsibility over the local electricity infrastructure would be far more preferable.

This model is applicable beyond Puerto Rico—it could benefit other islands in the tropics and subtropics, as well as polar regions and other areas that have weak or no grid connections. For those locales, it no longer makes sense to invest millions or billions of dollars to extend and maintain a centralized electric system. Thanks to the advance of solar, power electronics, control, and energy-storage technologies, community-based, distributed-energy initiatives are already challenging the dominant centralized energy model in many parts of the world. More than two years after Hurricane Maria, it's finally time for Puerto Rico to see the light. ■

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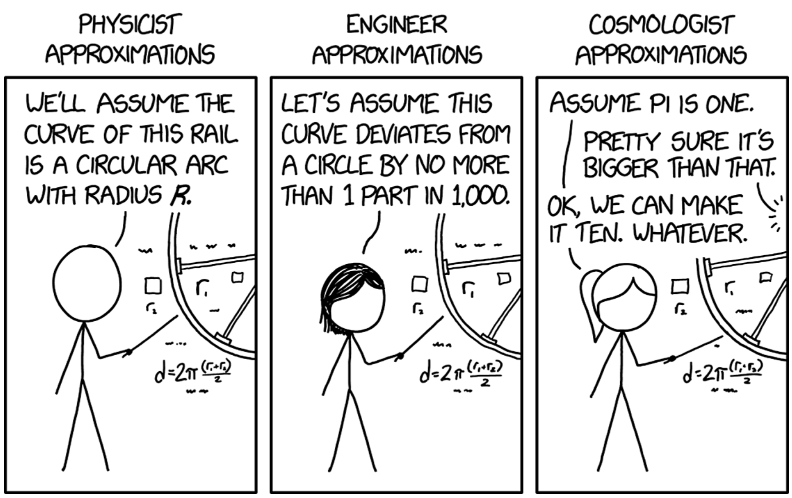

XKCD.COM

CONTINUED FROM PAGE 18 | passed around. So I said, "Well, if you like these things, I can draw more."

M.A.: You put disclaimers in all your books never to try your crazy ideas at home. Nevertheless, have you had fans who did try them out?

R.M.: The nice thing about the kinds of problems I tackle is they're, for the most part, thought experiments that would have large practical barriers to trying them out—like altering the rotation of the Earth to get to your meetings faster. A lot of the time, I will steer clear of questions that are easy to try and dangerous to do.... But I do have a few chapters with some practical advice. I have a section on how to take a selfie backlit against the moon—or even the sun if they have the right filter. It just takes a huge amount of coordination and organization. I took it to an extreme, too. In principle, if [someone pointing a telephoto lens at you was] several miles away, you could take a photo of yourself, probably on a mountaintop, in front of the disk of Jupiter. It'd involve traveling to find two mountaintops that are aligned just right. But I think someone could do it. I don't know if anyone has done it.... I did include the Jupiter and Venus examples [in *How To*] because I do hope someone tries it and posts their results online.... Talking about how I work, one of the easiest questions to ask is, What happens if you extend something in this direction or that? Looking at those extremes can get you a better idea of how the thing behaves overall. And often those are also the most fun and vivid examples to think about. Physics is full of atoms and black holes, partly because they represent two extremes of massiveness. And everything else falls between.

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Faculty Positions

Baylor University is a private Christian university and a nationally ranked research institution, consistently listed with highest honors among The Chronicle of Higher Education's "Great Colleges to Work For." The University is recruiting new faculty with a deep commitment to excellence in teaching, research and scholarship. Baylor seeks faculty who share in our aspiration to become a tier one research institution while strengthening our distinctive Christian mission as described in our strategic vision, Pro Futuris, (**www.baylor.edu/profuturis/**) and academic strategic plan, Illuminate (baylor.edu/illuminate). As the world's largest Baptist University, Baylor offers over 40 doctoral programs and has more than 17,000 students from all 50 states and more than 85 countries.

Baylor seeks to fill the following two faculty position within the Electrical and Computer Engineering Department: (i) Tenured/Tenure-Track Assistant/Associate/Full Professor and (ii) Clinical Assistant/Associate Professor. For tenured/tenure-track faculty, applicants must possess an earned doctorate and an active research agenda in the area of wireless and microwave circuits and systems. For clinical faculty, applicants must possess an earned masters or doctorate degree, extensive industry experience, and demonstrate the potential for excellent teaching. The ECE department offers B.S., M.S., M.E., and Ph.D. degrees and is rapidly expanding its faculty size, with current focus areas in wireless & microwave, biomedical, computer, cyber-physical, materials, and sustainable energy. Facilities include the Baylor Research and Innovation Collaborative (BRIC), a newly-established research park minutes from the main campus.

Applications will be considered on a rolling basis until the January 1, 2020 deadline. Applications must include:

1) a letter of interest that identifies the applicant's anticipated rank,
2) a complete CV,
3) a concise statement of research agenda (tenure track only),
4) a concise statement of teaching interests, and
5) the names and contact information for at least four professional references.

Additional information is available at **www.ecs.baylor.edu**. Should you have any questions on the position, feel free to contact the search chair, Dr. Keith Schubert at keith_schubert@baylor.edu. Materials will be submitted through Interfolio. For a direct link to the application portal, please go to jobs.baylor.edu

Baylor University is a private not-for-profit university affiliated with the Baptist General Convention of Texas. As an Affirmative Action/ Equal Opportunity employer, Baylor is committed to compliance with all applicable anti-discrimination laws, including those regarding age, race, color, sex, national origin, marital status, pregnancy status, military service, genetic information, and disability. As a religious educational institution, Baylor is lawfully permitted to consider an applicant's religion as a selection criterion. Baylor encourages candidates of the Christian faith who are women, minorities, veterans, and individuals with disabilities to apply.

THE UNIVERSITY OF NEW MEXICO

Faculty Positions in Electrical and Computer Engineering

The Department of Electrical and Computer Engineering in the School of Engineering at the University of New Mexico invites applicants to fill tenure-track faculty positions at the Assistant or Associate Professor level to begin in Fall 2020. Our focus areas, contingent upon funding, are:

- Applied Electromagnetics with emphases in pulsed power, high power RF, high energy density plasmas, novel computational techniques for multiscale electromagnetics modeling, RF circuits/systems, antennas, and wireless communications (physical layer).
- Quantum computing algorithms and architecture, and quantum enhanced systems, sensing and networks.
- Security including smart grid security, securing critical infrastructure, binary host and communication analysis, the current state of malware defenses, and industrial control system security.
- Autonomy with emphasis on integration of learning and control, cyber-physical systems with learning-enabled components, formal assurances, and intelligent decision making.

The department has state-of-the-art facilities, and its proximity facilitates collaboration with Sandia National Laboratories, Los Alamos National Laboratory, and the Air Force Research Laboratory. The research expenditures of ECE and associated research centers are over $30 million/year.

The minimum requirement is a doctorate by the time of appointment in electrical engineering, computer engineering, or closely related fields.

The preferred qualifications are a solid publication record, the potential for excellent teaching at the undergraduate and graduate levels, the potential to develop an externally funded research program, and a demonstrated commitment to diversity, equity, inclusion, and student success, as well as working with broadly diverse communities.

More information can be found at

http://ece.unm.edu/about/facultyjobs.html.

All qualified applicants are encouraged to apply, including women, minorities and those from other underrepresented groups. Candidates should apply electronically at **https://hr.unm.edu/unmjobs**, requisition number req10644.

Please submit an application letter indicating your area of interest, statements of research and teaching, a commitment to diversity statement, CV, and the contact information of three references. Applicants who are appointed to a UNM continuing faculty position are required to provide official certification of successful completion of all degree requirements before their initial employment with UNM.

For full consideration, applications should be submitted before December 1st, 2019.

The University of New Mexico is a family-friendly and an equal employment opportunity/affirmative action employer, making decisions without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, age, veteran status, disability, or any other protected class. We are committed to hiring and retaining a diverse workforce.

The University of New Mexico is a recipient of an ADVANCE Institutional Transformation grant from NSF to promote and advance women and minority faculty in STEM fields, and SOE is partnering with the ADVANCE at UNM program to help recruit and retain an excellent and diverse faculty.

Albuquerque is a beautiful and historic city with terrific weather, rich cultural life, and lots of outdoor activities. Cradled in the Rio Grande Valley beneath the Sandia Mountains, Albuquerque is by far the largest city in the state, acting as the media, educational, and economic center of New Mexico. For more information go to **https://advance.unm.edu/why-abq/**

BITS Pilani
Pilani | Dubai | Goa | Hyderabad

BITS Pilani, India
Announcement for faculty positions
in Electrical & Electronics and Computer Science Engineering

LOOKING FOR: HIGH ACHIEVERS

BITS Pilani, announced by MHRD, Govt. of India to be an Institute of Eminence (IoE) and ranked within World top 500 subject Ranking in Electrical & Electronics Engineering along with Computer Science Engineering by QS, is looking actively for accomplished researchers in all areas of Electrical & Electronics Engineering, Communication engineering as well as in relevant interdisciplinary domains covering cutting-edge complementary areas of scientific importance. Individuals with expertise in Data Science, AI, Information Security, Theoretical Computer Science, and High Performance Computing are also encouraged to apply. The candidates are expected to have predilection for teaching courses in the latest technology.

These faculty positions are open for **Pilani, Goa, Hyderabad and Dubai** campuses of BITS Pilani. An individual with a PhD degree in relevant discipline (EEE/ECE/CSE) may apply for the positions of Assistant Professor, Associate Professor and Professor. Overseas Citizens of India (OCIs), Persons of Indian Origin (PIOs) and foreign nationals are also encouraged to apply.

BITS Pilani provides its faculty competitive salary and benefits comparable to the best in the country. Startup and contingency funds are also provided to support research.

For detailed information on pay package & benefits and to apply through the online portal visit us at www.bits-pilani.ac.in/facultypositions

Applications received are reviewed periodically for further processing.

innovate achieve lead

University of Missouri

Assistant, Associate, Full Professors In Cyber Security & High Assurance Computing

The Department of Electrical Engineering and Computer Science at the University of Missouri seeks applications for five tenure-track/tenured positions at the rank of Assistant, Associate, and Full Professor, starting Fall 2020. These five positions are part of a University of Missouri strategic initiative in Cyber Security and complement recent hiring in that area. Applicants must have a Ph.D. in Computer Science, Computer Engineering or a closely related field. Preferred candidates will have success in research, and a strong commitment to excellence in teaching. For a candidate seeking a position at the level of Associate or Full Professor, a record of attracting external research funding appropriate to their rank is an essential factor. We also encourage applicants with a history of, or an interest in, interdisciplinary research. The focus of these hires will be in Cyber Security, broadly construed, including formal methods, systems, and theory.

We are especially interested in: Hardware and Embedded Systems Security, Secure Software Engineering (including static binary analysis, language-based security, and software verification), Wireless Security, Cloud Security, Cyber-Physical Systems and Internet of Things.

Applications will be reviewed immediately upon receipt and will continue until the positions are filled.

Application: Applicants should submit a CV, a research plan, a teaching statement and a list of three to five professional references electronically to **https://hrs.missouri.edu/find-a-job/academic** refer to Job ID **31546**.

Inquiries can be directed to the search committee at **securityhiring@missouri.edu**.

The University of Missouri is a Tier I research institution and one of only 60 public and private U.S. universities invited to membership in the prestigious Association of American Universities. The university was founded in 1839 in Columbia as the first public university west of the Mississippi River.

MU specifically invites and encourages applications from qualified women and members of groups underrepresented in science. Equal Opportunity/Affirmative Action/ADA employer firmly committed to fostering ethnic, racial, and gender diversity in our faculty.

University of Minnesota

Electrical and Computer Engineering, University of Minnesota – Twin Cities (https://ece.umn.edu/) invites applications for faculty positions in Communications, Networking, and Data Science.

The Department of Electrical and Computer Engineering is fully committed to a culturally and academically diverse faculty; candidates who will further expand that diversity are particularly encouraged to apply. An earned doctorate in an appropriate discipline is required. Rank and salary will be commensurate with qualifications and experience. Applications will be considered as they are received. Applications will be accepted until the positions are filled, but for full consideration, please apply by the priority deadline of **December 15, 2019**.

Additional information can be found on-line at **https://z.umn.edu/ecefacultyjobs**

To be considered for a position, candidates must apply on-line at: **https://humanresources.umn.edu/jobs** and search for the Job ID No. 333489.

The University of Minnesota is an equal opportunity educator and employer.

PRINCETON UNIVERSITY

The Department of Electrical Engineering seeks applications in all areas of Electrical Engineering for a tenure-track assistant professor faculty position. Candidates should have a commitment to teaching and a demonstrated ability to pursue a high impact research program. A start date of September 1, 2020 is preferred.

The department is committed to fostering an academic environment that acknowledges and encourages diversity and differences. The successful candidate will pursue academic excellence in diverse, multicultural, and inclusive settings.

Applicant review will begin in November. For full consideration, please submit applications no later than December 31, 2019, using the following site: **https://www.princeton.edu/acad-positions/position/1346**1. Applications require: a cover letter, complete curriculum vitae, descriptions of research and teaching interests, and the contact information for four references.

Princeton University is an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, national origin, disability status, protected veteran status, or any other characteristic protected by law. The selected candidate will be required to successfully complete a background check.

ILLINOIS

ISE | Industrial & Enterprise Systems Engineering

GRAINGER COLLEGE OF ENGINEERING

Teaching/Clinical Professor in Health Technology (Open Rank)

The Department of Industrial & Enterprise Systems Engineering at the University of Illinois at Urbana-Champaign invites applications for a Teaching/Clinical Professor (Open Rank) position to teach graduate and undergraduate courses in the areas of health-care technology and systems. The candidate will lead the curriculum development for engineering courses offerings for a proposed MS in Health Technology (MSHT) being developed in collaboration with the College of Applied Health Sciences. The candidate will create new courses in hardware and software design for the MSHT program and assist in the development of a new 'makerspace' laboratory. In addition to teaching and contributing to the laboratory, the successful candidate will hold office hours and provide academic advising to a subset of students in the department.

Please visit http://jobs.illinois.edu to view the complete position announcement and application instructions. For full consideration, apply by November 1, 2019. The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer. Illinois is an EEO Employer/Vet/Disabled - www.inclusiveillinois.illinois.edu

Multiple Tenure Faculty Positions in Computer Science and Engineering

Applications are invited for multiple tenure-track positions at the Assistant, Associate and/or Full Professor levels across all areas of Computer Science and Engineering. The department is looking to grow rapidly in different areas, with the possibility of cluster hires in each area. We are particularly looking to fill multiple positions in: Theoretical Computer Science: All areas will be considered, including quantum computing, cryptography, algorithms and complexity. Computer Systems and Architecture: Candidates working at all layers of the system stack will be considered. We offer a top 10 ranked systems research department (as per csrankings.org) and unique collaboration opportunities with faculty spanning both computer science and computer engineering in one unified department. Data Science: All areas of machine learning, Artificial Intelligence, and data science will be considered, including theory, NLP, computer vision, robotics, optimization, and fairness, and applications to scientific data. Computer Security: All areas of computer security will be considered, including software security, systems and hardware security, network security, and applied cryptography. We offer a top 10 ranked security research environment (as per csrankings.org) across these disciplines. Applicants should hold a Ph.D. in computer science, computer engineering, or a closely related field that must be completed by the start date of the position. All applicants should be committed to excellence in both research and teaching and those considered for the Associate and Full level must demonstrate an established record in research. Our department, and the University as a whole, provides unusually rich collaboration opportunities due to a large, diverse range of colleges and departments, numerous venues for inter-departmental colloquia and the like, and excellent internal support for successful grantsmanship. We expect our hires to establish a strong research program, supervise graduate and undergraduate students, and teach relevant undergraduate and graduate courses. We strongly encourage applicants from underrepresented groups, and dual career couples. Applicants should submit a detailed curriculum vita listing all publications, research and teaching statements, and the names and email addresses of four references. Full consideration will be given to applications submitted by January 1, 2020 though applications will continue to be accepted until all positions are filled. E-mail your questions regarding the application process to recruiting@cse.psu.edu. Penn State is a premier public research, land grant university. The Department of Computer Science and Engineering is part of the School of EECS in the College of Engineering. We are looking for candidates who will add to the department's diverse culture and research strengths. Penn State is committed to and accountable for advancing diversity, equity and inclusion in all its forms. We embrace individual uniqueness, foster a culture of inclusion that supports both broad and specific diversity initiatives, and leverage the educational and institutional benefits of diversity. We value inclusion as a core strength and an essential element of our public service mission. Penn State's College of Engineering strives to build a welcoming, inclusive, and supportive environment for students, staff, and faculty. We rely on the expertise, sensitivity and commitment of an inclusive faculty to enhance diversity, seek equity, and create a welcoming environment within our community. We are committed to nurturing a learning and working environment that respects differences in culture, age, gender, race, ethnicity, physical ability, sexual orientation, and religious affiliation. In welcoming every candidate, we strive to meet the needs of professional families by actively assisting with partner-placement needs. We are inspiring change and impacting tomorrow. The University is in the beautiful town of State College, which is ranked one of the best college towns in the U.S. The area offers a wide variety of cultural and outdoor recreational activities, and outstanding University events, from collegiate sports to fine arts productions. The public-school system is excellent, with a nationally ranked high school by U.S. News and World Report.

Apply online at https://apptrkr.com/1617800

CAMPUS SECURITY CRIME STATISTICS: For more about safety at Penn State, and to review the Annual Security Report which contains information about crime statistics and other safety and security matters, please go to http://www.police.psu.edu/clery/, which will also provide you with detail on how to request a hard copy of the Annual Security Report.

Penn State is an equal opportunity, affirmative action employer, and is committed to providing employment opportunities to all qualified applicants without regard to race, color, religion, age, sex, sexual orientation, gender identity, national origin, disability or protected veteran status.

Department of Electrical and Computer Engineering
Graduate School of Engineering and Management
Air Force Institute of Technology (AFIT)
Dayton, Ohio

Faculty Position

The Department of Electrical and Computer Engineering at the Air Force Institute of Technology is seeking applications for a tenured or tenure-track faculty position. All academic ranks will be considered. Applicants must have an earned doctorate in Electrical Engineering, Computer Engineering, Computer Science, or a closely affiliated discipline by the time of their appointment (anticipated 1 September 2020).

We are particularly interested in applicants specializing in one or more of the following areas: autonomy, artificial intelligence / machine learning, navigation with or without GPS, cyber security, and VLSI. Candidates in other areas of specialization are also encouraged to apply. This position requires teaching at the graduate level as well as establishing and sustaining a strong DoD relevant externally funded research program with a sustainable record of related peer-reviewed publications.

The Air Force Institute of Technology (AFIT) is the premier Department of Defense (DoD) institution for graduate education in science, technology, engineering, and management, and has a Carnegie Classification as a High Research Activity Doctoral University. The Department of Electrical and Computer Engineering offers accredited M.S. and Ph.D. degree programs in Electrical Engineering, Computer Engineering, and Computer Science as well as an MS degree program in Cyber Operations.

Applicants must be U.S. citizens. Full details on the position, the department, applicant qualifications, and application procedures can be found at ***http://www.afit.edu/ENG/*** . Review of applications will begin on January 6, 2020. The United States Air Force is an equal opportunity, affirmative action employer.

Micron Technology, Inc., is seeking the below positions for its semiconductor R&D facility in Boise, ID; its manufacturing facility in Manassas, VA; and its sales and design facilities in Folsom and Milpitas, CA; and design facilities in Austin, TX and Longmont, CO; and worksites in Irvine, CA; Novi, MI; and Allen, TX.

The following Micron subsidiaries are also seeking positions: Micron Semiconductor Products, Inc., at its headquarters in Boise, ID; and sales facilities in Meridian, ID; and Folsom and Milpitas, CA.

Electrical, Electronics, Communications, Chemical, Industrial, Mechanical, Materials, Computer System Analysts, and Software Engineering; Physics, Materials Science, Engineering Manager and other related Engineering occupations. Marketing, Sales, Logisticians, Finance, Accounting, and other related business positions.

Please submit your resume online:
http://www.micron.com/jobs

Resume and/or cover letter must reflect each requirement or it will be rejected. Upon hire, all applicants will be subject to drug testing/screening and background checks.

Note: Some of these positions may require domestic and international travel for brief business purposes. Please read the full job description when applying online for such requirements.

EOE

OPUS College of Engineering
MARQUETTE UNIVERSITY

The Department of Electrical and Computer Engineering (ECE) at Marquette University is seeking candidates for a tenure-track faculty position in Computer Engineering starting in August 2020. Appointment will be at the assistant professor level. Faculty duties include teaching at the undergraduate and graduate levels, research, and supervision of graduate students. Candidates with expertise in computer network security, secure wireless communications, Internet-of-Things (IoT) security, software defined networks, 5G MAC layer, and AI/ machine learning in communication systems and networks will be given special consideration. Faculty appointments require completed doctoral degree in Computer Engineering or closely related field.

The ECE Department has 15 tenured/tenure track faculty and over 200 undergraduate and 60 graduate students. We offer ABET accredited B.S. degree in Electrical Engineering and B.S. degree in Computer Engineering. Graduate degrees include Five-year B.S./ M.S., M.S., and Ph.D. degrees.

Marquette University, an Equal Opportunity Employer, is a family friendly university with a passion for furthering the cause of diversity and inclusion. Those from underrepresented groups are encouraged to apply.

Please submit a complete application by December 15, 2019. Review of applications will continue until the position is filled. For further information and for the application go to **https://employment.marquette.edu/postings/12290**.

UCD DUBLIN

University College Dublin's School of Electrical & Electronic Engineering has a long and distinguished record of excellence in education and research. The School has an international track record of achievement across major fields of research including biomedical engineering, communications and integrated circuits, optimisation and control, and electrical power systems (**http://www.ucd.ie/eleceng/**). The School is committed to the highest standards of teaching, learning and student development within a research-informed environment.

Applications are invited for the position of Associate Professor in Biomedical Engineering in the area of biomedical signals and sensors. Applications are particularly encouraged from individuals whose research can integrate with research in the School in robotics, wearable sensing and neural engineering.

Candidates should have an outstanding record of research accomplishment in fundamental scientific areas underpinning Biomedical and Electronic Engineering, and experience in the delivery of high quality research-informed teaching to doctoral level.

The appointee will be expected to build and sustain an internationally high-profile research team, contribute to Bachelors and Masters degree programmes in Biomedical and Electronic Engineering, and interact with other disciplinary areas within and outside of the university.

Closing date: 16 December 2019

Full details can be found at **https://www.ucd.ie/workatucd/**

University College Dublin is an Equal Opportunity Employer.

LEHIGH UNIVERSITY | P.C. ROSSIN COLLEGE OF ENGINEERING AND APPLIED SCIENCE

The Electrical and Computer Engineering Department of the P.C. Rossin College of Engineering & Applied Science at Lehigh University invites applications for **one tenure track position and one professor of practice position in the general areas of computer engineering,** including but are not limited to: embedded and real time systems, energy-efficient architectures, cyber-physical systems, machine learning accelerators, hardware security, accelerators for bioinformatics, and edge computing. Review of applications will begin in **early December**, and will continue until the positions are filled. See **https://engineering.lehigh.edu/ece/about-department-electrical-and-computer-engineering/ece-job-openings** for details.

PURDUE UNIVERSITY

The School of Electrical and Computer Engineering at Purdue University is seeking applications for tenure-track positions at the Assistant or Associate Professor level in Computer Engineering. We are particularly interested in candidates in computer systems and security. Successful candidates must hold a Ph.D. degree in Electrical and Computer Engineering, Computer Science, or a related discipline. A background check will be required for employment in this position. Submit applications online **https://tinyurl.com/purdue-ecesystems2019** Purdue University is an EOE/AA employer. All individuals, including minorities, women, individuals with disabilities, and veterans are encouraged to apply.

UNIVERSITY OF TEXAS ARLINGTON

CHAIR, DEPARTMENT OF ELECTRICAL ENGINEERING

Arlington, TX

The Electrical Engineering Department at The University of Texas at Arlington seeks nominations and applications for Department Chair. Applicants should possess excellent leadership and interpersonal skills and have a strong record of scholarship and teaching commensurate with appointment as Professor. Qualified candidates will be considered for the Janet and Mike Greene Endowed Professorship.

Duties and Responsibilities
The Chair is expected to provide vision and leadership in building focused research programs and enhancing collaborative research within and outside the University, enhancing student enrollment in general and international enrollment specifically and fostering relationships with industry and federal organizations. The Chair will also play an important role in ensuring that the Department is aligned with the four themes of UTA's Strategic Plan (Health and the Human Condition, Data-Driven Discovery, Sustainable Urban Communities and Global Environmental Impact) and, by extension, the College's Strategic Plan.

Preferred Qualifications
Applicants must have earned a Ph.D degree in electrical engineering or a related field and have a significant level of teaching, research and scholarship accomplishments commensurate with the rank of full professor with tenure. Qualified candidates should have an exceptional record of scholarly research, and be highly recognized for their technical contributions and leadership in their areas of expertise.

The University, College and Department
The University of Texas at Arlington (**https://www.uta.edu**) is a Carnegie Research-1 "highest research activity" institution and is located in the Dallas-Fort Worth Metroplex, a fast-growing region that offers excellent cultural, recreation, and entertainment opportunities. With a projected global enrollment of more than 58,000 in 2019-20, UTA is the largest institution in The University of Texas System. The University is a Hispanic-Serving Institution and was ranked as the seventh-best nationally and top four-year college in Texas for veterans on *Military Times*' 2019 Best for Vets list. The College of Engineering (**https://www.uta.edu/engineering**) is home to seven departments: Bioengineering; Civil Engineering; Computer Science and Engineering; Electrical Engineering; Industrial, Manufacturing, and Systems Engineering; Materials Science and Engineering; and Mechanical and Aerospace Engineering. With more than 7,500 students, the College is among the largest in Texas and offers the most comprehensive engineering degree programs in the region. It offers 11 baccalaureate, 14 master's, and 9 doctoral degree programs and has ties to numerous Fortune 500 companies in the region. The College is enjoying growth in student enrollment and student graduation, which has been concomitant with growth in research expenditures – more than $40 million last year – collaboration, innovation and entrepreneurship by faculty and students. The Electrical Engineering Department (**https://www.uta.edu/ee**) has strong educational and research programs, with 25 tenured/tenure track faculty members. The faculty includes 1 member of the National Academy of Engineering, 3 members of the National Academy of Inventors, 9 IEEE Fellows, 9 OSA and SPIE Fellows, and two active NSF CAREER awardees. In fall 2019 enrollment included more than 440 undergraduate students and more than 230 graduate students. Annual research expenditures exceed $5 million, with world-class research in controls and robotics, MEMS and sensors, optics and nanophotonics, communication systems, power conversion and control systems. The faculty are also engaged in interdisciplinary research activities in outstanding facilities such as the Shimadzu Institute Nanotechnology Research Center, the Science & Engineering Innovation & Research, or SEIR, Building, which opened in August 2018, the Smart Hospital, and the UTA Research Institute (UTARI).

Application Instructions
Screening of complete applications will begin immediately and continue until the completion of the search process. Inquiries, nominations, referrals, and applications (cover letter, curriculum vitae, vision statement, and statements of research and teaching objectives) should be submitted via the Isaacson, Miller website for the search:
http://www.imsearch.com/7229.

EEO/AA Policy
UTA is an Equal Opportunity/Affirmative Action institution. Minorities, women, veterans and persons with disabilities are encouraged to apply. Additionally, the University prohibits discrimination in employment on the basis of sexual orientation. A criminal background check will be conducted on finalists. UTA is a tobacco free campus.

ISAACSON, MILLER

USC Viterbi
School of Engineering
Ming Hsieh Department of Electrical and Computer Engineering

University of Southern California Faculty Positions Ming Hsieh Department of Electrical and Computer Engineering

The Ming Hsieh Department of Electrical and Computer Engineering (**https://minghsiehece.usc.edu/**) of the USC Viterbi School of Engineering (**https://viterbischool.usc.edu**) seeks outstanding faculty candidates for multiple faculty positions at any tenure-track or tenured rank. The Viterbi School is committed to increasing the diversity of its faculty and welcomes applications from women, persons from underrepresented groups, veterans, and individuals with disabilities.

Candidates of exceptional academic quality from all areas of electrical and computer engineering at all ranks are encouraged to apply.

Faculty members are expected to teach undergraduate and graduate courses, supervise undergraduate, graduate, and post-doctoral researchers, and develop a strong funded research program. Applicants must have a Ph.D. or the equivalent in electrical engineering or a related field and a strong research and publication record. Applications must include a letter clearly indicating area(s) of specialization, a detailed curriculum vitae, a concise statement of current and future research directions, and contact information for at least four professional references. Applicants should also include a succinct statement on fostering an environment of diversity and inclusion. This material should be submitted electronically at **https://minghsiehece.usc.edu/jobs/**

Applications should be submitted by **December 15, 2019**, as applications received after this date may not be considered.

USC Viterbi School of Engineering is among the top tier of engineering schools in the world. It has 188 full-time, tenure-track faculty members, and is home to the Information Sciences Institute. Research expenditures typically exceed $200 million annually. The School is affiliated with the Alfred E. Mann Institute for Biomedical Engineering, the Institute for Creative Technologies, and the USC Stevens Center for Innovation. Faculty affiliation is also possible with a new interdisciplinary research center comprised of scholars from across the University that focuses on the convergence of medicine and engineering in the development and application of neuroprosthetics.

Ming Hsieh Department of Electrical and Computer Engineering has a student body consisting of approximately 240 undergraduate students, 1100 M.S. students, and 330 Ph.D. students. The Department has a total of 59 full-time tenured and tenure-track faculty. Among our faculty, 7 are members of National Academy of Engineering; 2 are members of National Academy of Sciences; 9 are fellows of the American Association for Advancement of Science; 6 are fellows of the National Academy of Inventors, 3 are members of the American Academy of Arts and Sciences; 35 are IEEE fellows; and 7 have received IEEE gold medals.

USC is an equal opportunity, affirmative action employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, protected veteran status, disability, or any other characteristic protected by law or USC policy. USC will consider for employment all qualified applicants with criminal histories in a manner consistent with the requirements of the Los Angeles Fair Chance Initiative for Hiring ordinance. The Viterbi School of Engineering at USC is committed to enabling the success of dual career families and fosters a family-friendly environment.

桂林電子科技大学
GUILIN UNIVERSITY OF ELECTRONIC TECHNOLOGY

Full-Time Faculty Positions in Artificial Intelligence

School of Artificial Intelligence
Guilin University of Electronic Technology
Location: Guilin, Guangxi, China
Closing Date: unlimited

Opportunities

Applicants are invited for the positions of tenure track faculty in the School of Artificial Intelligence (SAI) at Guilin University of Electronic Technology (GUET). SAI is seeking candidates who have an interest in pursuing innovative and interdisciplinary education programs, and in leading research efforts in Artificial Intelligence, including but not limited to Machine Learning, Image Processing, Computer Vision, Natural Language Processing, Big Data, and Autonomous Robotics. Applicants should possess Ph.D. degrees in Computer Science, Electrical Engineering, Electrical and Computer Engineering, or related fields with demonstrated records and potentials for research, teaching and leadership.

This is a worldwide search, open to qualified candidates from all countries and of all nationalities. A globally competitive package will be offered.

About GUET

As one of the four famous universities focusing on electronic technology in China, GUET is a key public university which is supported by the Ministry of Industry and Information Technology and Guangxi Zhuang Autonomous Region. Founded in 1960, the University now has 4 doctoral programs, 1 postdoctoral research center, 17 master programs and 70 bachelor programs. GUET owns over 2,900 faculty and staff, and 40,600 students at all levels.

About Guilin

Boasting a long-standing history of more than 2,000 years, due to the uniqueness of wonders of mountains and rivers, Guilin enjoys a high prestige as “East or west, Guilin’s landscape is best”, ranking 2nd amongst China’s top 10 scenic spots. Guilin Lijiang River makes the list in the world’s 15 best rivers for travelers by CNN in 2013. Numerous tourists, including heads of states, celebrities at home and abroad, have attracted by Guilin’s sceneries.

Way to Apply

Send a resume to zhaopin@guet.edu.cn on the email’s subject of “Apply for AI”.

Contacts

Please do not hesitate to contact us if there is any assistance we could provide: School of Artificial Intelligence: Mr. Mo; Cell phone: + 86-13737731244. Department of Human Resources: Ms. Tung; Cell phone: + 86-13217735600.

We look forward to your joining us!

The Edward S. Rogers Sr. Department
of Electrical & Computer Engineering
UNIVERSITY OF TORONTO

Assistant Professor, Teaching Stream – Electrical and Computer Engineering

The Edward S. Rogers Sr. Department of Electrical and Computer Engineering (ECE) at the University of Toronto invites applications for a full-time teaching stream faculty appointment at the rank of Assistant Professor, Teaching Stream, in the general area of Computer Systems and Software. The appointment will commence on **July 1, 2020**, or shortly thereafter.

Applicants must have a Ph.D. in Electrical and Computer Engineering, or a related field, at the time of appointment or soon after. The successful candidate will have demonstrated excellence in teaching and pedagogical inquiry, including in the development and delivery of undergraduate courses and laboratories, curriculum development, and supervision of undergraduate design projects. This will be demonstrated by strong communication skills, a compelling statement of teaching submitted as part of the application highlighting areas of interest, awards and accomplishments and teaching philosophy; sample course syllabi and materials; and teaching evaluations, as well as strong letters of reference from referees of high standing endorsing excellent teaching and commitment to excellent pedagogical practices and teaching innovation.

Eligibility and willingness to register as a Professional Engineer in Ontario is highly desirable.

Salary will be commensurate with qualifications and experience.

The Edward S. Rogers Sr. Department of Electrical and Computer Engineering at the University of Toronto ranks among the best in North America. It attracts outstanding students, has excellent facilities, and is ideally located in the middle of a vibrant, artistic, diverse and cosmopolitan city. Additional information may be found at **http://www.ece.utoronto.ca**.

Review of applications will begin after **October 9, 2019**, however, the position will remain open until **December 2, 2019**.

As part of your online application, please include a cover letter, a curriculum vitae, and a teaching dossier including a summary of your previous teaching experience, your teaching philosophy and accomplishments, your future teaching plans and interests, sample course syllabi and materials, and teaching evaluations. Applicants must arrange for three letters of reference, including at least one primarily addressing the candidates teaching, to be sent directly by the referees (on letterhead, signed and scanned), by email to the ECE department at **search2019@ece.utoronto.ca**. Applications without any reference letters will not be considered; it is your responsibility to make sure your referees send us the letters while the position remains open.

You must submit your application online while the position is open, by following the submission guidelines given at **http://uoft.me/how-to-apply**. Applications submitted in any other way will not be considered. We recommend combining attached documents into one or two files in PDF/MS Word format. If you have any questions about this position, please contact the ECE department at **search2019@ece.utoronto.ca**.

The University of Toronto is strongly committed to diversity within its community and especially welcomes applications from racialized persons / persons of colour, women, Indigenous / Aboriginal People of North America, persons with disabilities, LGBTQ persons, and others who may contribute to the further diversification of ideas.

As part of your application, you will be asked to complete a brief Diversity Survey. This survey is voluntary. Any information directly related to you is confidential and cannot be accessed by search committees or human resources staff. Results will be aggregated for institutional planning purposes. For more information, please see **http://uoft.me/UP**.

All qualified candidates are encouraged to apply; however, Canadians and permanent residents will be given priority.

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

Junior Faculty Position in the Department of Electrical Engineering

Columbia Engineering is pleased to invite applications for a faculty position in the Department of Electrical Engineering at Columbia University in the City of New York. Applications for Junior rank will be considered.

The Electrical Engineering department welcomes applications in all areas of electrical engineering. Candidates must have a Ph.D. or its professional equivalent by the starting date of the appointment. Applicants for this position must demonstrate the potential to do pioneering research and to teach effectively. The Department is especially interested in qualified candidates who can contribute, through their research, teaching, and/or service, to the diversity and excellence of the academic community.

The successful candidate is expected to contribute to the advancement of their field and the department by developing an original and leading externally funded research program, and to contribute to the undergraduate and graduate educational mission of the Department. Columbia fosters multidisciplinary research and encourages collaborations with academic departments and units across Columbia University. The Department actively participates in the school-wide Engineering for Humanity initiatives that relate to engineering and medicine, autonomous systems, quantum computing and technology, and sustainability.

For additional information and to apply, please see: **http://engineering.columbia.edu/faculty-job-opportunities**. Applications should be submitted electronically and include the following: curriculum vitae including a publication list, a description of research accomplishments, statements of research and teaching interests and plans, contact information for three experts who can provide letters of recommendation, and up to three pre/reprints of scholarly work. All applications received by December 1st, 2019 will receive full consideration. We will accept and review applications after this date.

Applicants can consult **http://www.ee.columbia.edu** for more information about the department and **http://pa334.peopleadmin.com/postings/4208** for more details on the position and application.

Columbia University is Equal Opportunity Employer / Disability / Veteran

COLLEGE OF ENGINEERING
ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF MICHIGAN

THE ELECTRICAL AND COMPUTER ENGINEERING (ECE) Division of the Electrical Engineering and Computer Science Department at the University of Michigan, Ann Arbor invites applications for junior or senior faculty positions, especially from women and under-represented minorities.

Successful candidates will have a relevant doctorate or equivalent experience and an outstanding record of research in academia, industry and/or at national laboratories. They should have a strong record or commitment to teaching at undergraduate and graduate levels, to providing service to the university and profession, and to broadening the intellectual diversity of the ECE Division.

We invite candidates across all research areas to apply, with particular interest in machine learning, data science, computer engineering, and embedded systems.

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

Please see application instructions at:
https://ece.engin.umich.edu/people/faculty-positions/

The review of applications will begin **November 18, 2019** with full consideration given to candidates submitting by then.

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

UC RIVERSIDE UNIVERSITY OF CALIFORNIA | Marlan and Rosemary Bourns College of Engineering

Faculty Position for Full Professor (Tenured) and Center Director Winston Chung Global Energy Center (WCGEC) University of California, Riverside

The University of California, Riverside's (UCR) Marlan and Rosemary Bourns College of Engineering (BCOE) invites applicants for a tenured Full Professor position who will serve as the Director of the BCOE WCGEC, and will contribute meaningfully to the success of future teaching, research, and service accomplishments. The incumbent is expected to initiate and sustain a strong sponsored research and graduate training program. The successful candidate will be an outstanding senior faculty member or an industry leader with a proven record in the broad area of Energy Devices and Materials, focusing on related topics such as advanced and scalable battery technologies and others. The successful candidate will also demonstrate clear potential to lead the overall integrated multidisciplinary research efforts within the center in partnership with the related departments and programs.

Apply to the AP Recruit website at **https://aprecruit.ucr.edu/JPF01179**. Details and application materials can be found at **http://www.engr.ucr.edu/about/employment.html**. Review of applications will begin December 1, 2019, and the position is open until filled. Appointments are expected to begin July 1, 2020. Salary will be commensurate with experience. Advancement through the faculty ranks at the University of California is through a series of structured, merit-based evaluations, occurring every 2-3 years, each of which includes substantial peer input.

UCR is a world-class research university with an exceptionally diverse undergraduate student body. Its mission is explicitly linked to providing routes to educational success for underrepresented and first-generation college students. A commitment to this mission is a preferred qualification. EEO/AA/Disability/Vets Employer.

DIVISION OF WORK & INDUSTRY/NATIONAL MUSEUM OF AMERICAN HISTORY/SMITHSONIAN INSTITUTION

TIFFANY'S TRANSATLANTIC TELEGRAPHY DOODAD

On 16 August 1858, Queen Victoria and U.S. president James Buchanan said hello. The conduit of their exchange of pleasantries was the first transatlantic telegraph cable, which connected Newfoundland with Ireland across some 3,200 kilometers. The jeweler Tiffany and Co. sought to celebrate (and cash in on) what was touted as the communications event of the century. And so it bought up surplus cable from the project and turned it into souvenirs. Each 4-inch segment retailed for 50 cents (about US $15 today). Sadly, though, the cable itself was a flop. The queen's 98-word message took almost 16 hours to transmit. The quality of the transmission quickly degraded, and the cable failed entirely after just a few weeks. Tiffany was left with unsellable stock commemorating a failure, and transatlantic communication would wait another eight years for a new, more robust cable to be laid. ■

↗ **For more on the history of transatlantic cables, see https://spectrum.ieee.org/pastforward1119**