What's Fueling the Air-Taxi Craze › Is it the next aerospace bubble? P. 6

NASA's Fusion Power Shortcut › The design works without lasers or magnets P. 32

Why Robots Should Play Foosball › Brain-inspired circuits need real-world tests P. 44

FOR THE TECHNOLOGY INSIDER
MARCH 2022

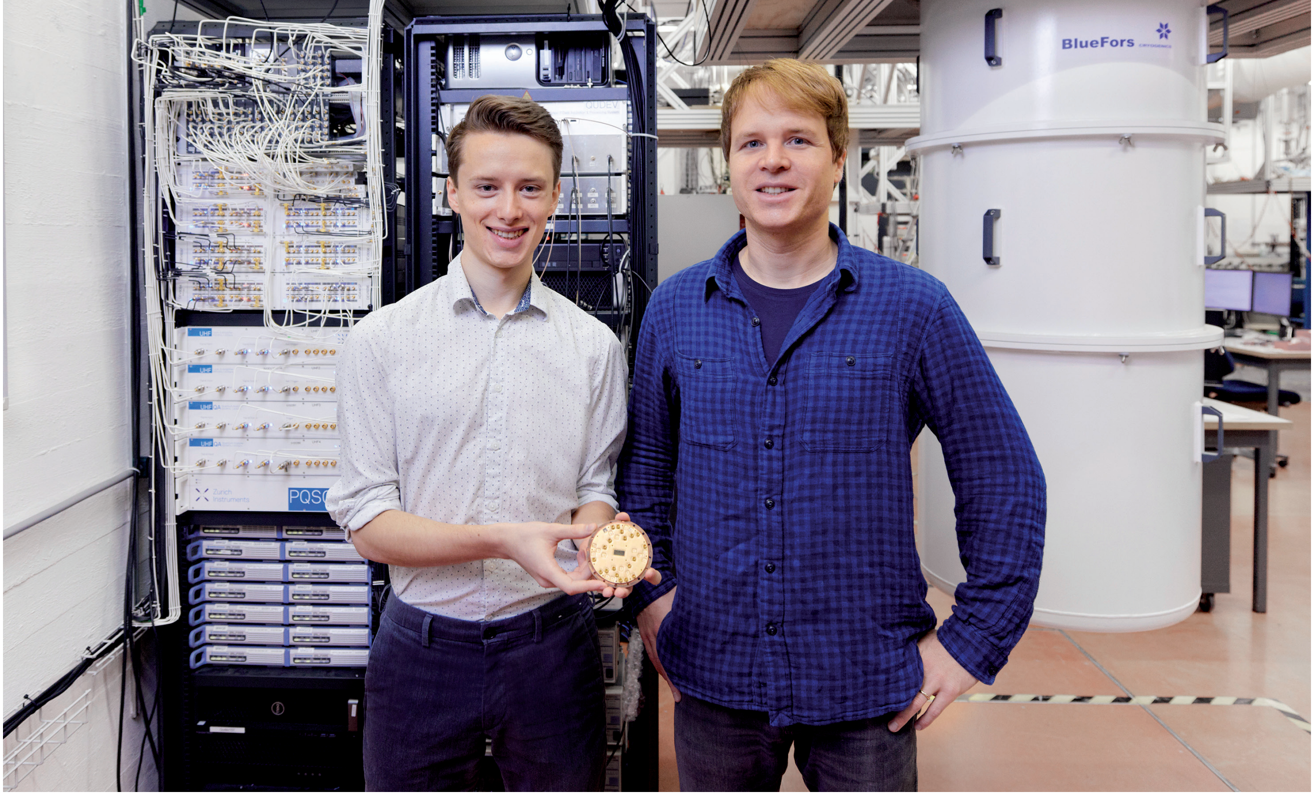
IEEE Spectrum

SPECIAL INVESTIGATION:

How People With Bionic Eyes Were Left in the Dark

Barbara Campbell used her retinal implant to help navigate her New York City commute—until it stopped working during a subway transfer.

IEEE



Nathan Lacroix and Sebastian Krinner, ETH Zurich

VOLUME 59 / ISSUE 3 MARCH 2022

Contents

ON THE COVER:
Photo by Nathaniel Welch/Redux

TOP: WESTERN SYDNEY UNIVERSITY; BOTTOM: WOODS HOLE OCEANOGRAPHIC INSTITUTION

BACK STORY

Dynamic Duo

Senior Editor Eliza Strickland [top] was dazzled when she heard about the first retinal implant approved to restore vision to the blind. That was back in 2011, when the system—the first commercial device to provide artificial vision by using electrodes to stimulate retinal cells—was approved in Europe and was poised for approval in the United States. While the vision was extremely crude, early adopters were told they'd get upgrades as the device's maker, Second Sight Medical Products, improved it.

But inventing a cutting-edge technology is no guarantee of market success. In 2019, Second Sight stopped selling its retinal implant, saying that it would focus instead on R&D for a brain implant. A year later, the company nearly went bankrupt and stopped communicating with customers. Users suddenly found themselves with obsolete and unsupported implants in their eyes, with little hope for repairs or replacements and no possibility of upgrades.

Strickland wanted to know what that experience was like for people who had put their faith in the company. She decided to pair her domain knowledge with the investigative firepower of Mark Harris [bottom], a Seattle-based freelance journalist who has written for *IEEE Spectrum* since 2010 and became a contributing editor in 2014. The two divided up the reporting, with Harris tracking down patients while Strickland interviewed clinicians and researchers. Harris also searched government databases and company filings: "It's always interesting to see what stories the data tell," he says.

The article that Strickland and Harris cowrote [p. 24] is a cautionary tale of "how the hype hit reality," Harris says. And as Strickland continues to cover next-generation neurotech companies, she'll ask questions inspired by her recent reporting on Second Sight. "I'll be asking engineers, what happens to patients if this technology doesn't work out?" she says. "What's the plan for them?" ■

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CONTRIBUTORS

LAWRENCE FORSLEY

Forsley is the deputy principal investigator for NASA's lattice confinement fusion project. In "NASA's New Shortcut to Fusion Power" [p. 32], he and coauthors Theresa Benyo, Bayarbadrakh Baramsai, and Bruce Steinetz, all contributors to the project, explain how their team has ignited fusion without powerful lasers or magnets. They hope the technique can someday power spacecraft, but as Forsley says, the most exciting part is experimenting with an entirely new form of fusion.

GREGORY COHEN

Cohen is an associate professor at the International Center for Neuromorphic Systems at Western Sydney University, in Australia. Early in his career, he tried—and mostly failed—to build a neuromorphic robot table-tennis player. "The robot only ever beat the human player by cheating," he says. It would play the sound of the ball hitting the table just before the real ball struck, flummoxing its opponent. Robot foosball players, described on page 44, should be more honorable opponents.

DEXTER JAGULA

Jagula works for SkyWatch, a company dedicated to making satellite imagery accessible. "Like many kids growing up, I wanted to become an astronaut," he says. But even after obtaining a master's from the International Space University, "that wasn't going to happen." So Jagula, a software engineer, did the next best thing. He cofounded SkyWatch with like-minded developers he met at the NASA Space Apps Challenge. Read about this burgeoning field in "A Boom With a View" [p. 38].

JULIANNE PEPITONE

Pepitone is a contributing editor who has worked with *IEEE Spectrum* since 2016. On page 10 of this issue, she reports on the twin dangers that e-waste presents: data insecurity and environmental harm. "Obsolescence is an inevitable part of the device life cycle," she says. "But we've got to find a way to better handle these piles of old laptops and phones."

A Delta IV rocket launched a spy satellite from Vandenberg Air Force Base in 2012.

SPECTRAL LINES

Your Eye in the Sky ›

Satellite reconnaissance comes in from the cold

BY GLENN ZORPETTE

For many techies, the Cold War was an exhilarating time to be alive. As the United States and the Soviet Union faced off in a half-century-long struggle for military, economic, cultural, and ideological dominance, the winner was technology.

Some of the most interesting tech was tucked away, or far away, from the view of ordinary folks. These were the cipher machines, the code-breaking supercomputers, and, especially, reconnaissance planes and satellites.

Today, you can buy or easily access all sorts of consumer tech that exceeds the capabilities of what used to be called National Technical Means. We don't know how powerful the National Security Agency's supercomputers were in the late 1980s, but consider the Cray Y-MP—introduced in 1988: It could sustain a rate of 2 gigaflops. Really hot stuff at the time. Pretty poky nowadays, though, when a garden-variety M1 Mac delivers 2.6 teraflops for roughly US $1,000.

But for glamour and intrigue, it's hard to beat a recon satellite. Overhead reconnaissance was at the heart of some of the most sensational crises of the Cold War—the "Missile Gap," the capture of U2 pilot Francis Gary Powers, the Cuban Missile Crisis, and the William Kampiles "Big Bird" spy scandal.

Kampiles sold to Soviet agents the user manual for the first KH-11 spy satellite, which was launched in 1976. The KH-11s pioneered the use of electronic sensors—charge-coupled devices—to capture images, which were transmitted to ground stations in near-real time. Previous spy satellites exposed photographic film and ejected film canisters in reentry capsules.

When I visited Kwajalein Atoll, a U.S. military test site, in 1986, an old intelligence hand told me a story whose possibly apocryphal nature won't stop me from repeating it here. It seems that in the late 1970s, some technicians at an intelligence facility in Texas, known to be of interest to the Soviets, decided to have some fun. They took a couple of hundred towels and arranged them on the ground to spell out, "IF YOU CAN READ THIS YOU ARE WHERE WE WERE 10 YEARS AGO." Or, more likely, «Если вы можете прочитать это, вы находитесь там, где мы были 10 лет назад.»

The resolution of the KH-11s has never been revealed, but it is thought to have been about 15 centimeters in the 1980s, depending on circumstances. That's better than what you can now get in the commercial realm, from the handful of companies selling reconnaissance images and services to anyone who wants them. That's because the U.S. government limits the resolution of commercially available reconnaissance images to 25 cm.

Nevertheless, a thriving commercial market has sprung up, as Dexter Jagula notes in "A Boom With a View," on page 38. Companies including 21AT, Airbus, Maxar, and Planet are all offering images with resolution down to about 30 cm.

Image-processing software and other enhancements may have endowed the current crop of KH-11 satellites with resolving power as good as 10 cm. Confidence in this figure arises from several different factors, not least a single reconnaissance image tweeted by then-president Donald Trump on 30 August 2019. The image, of an Iranian rocket-launch facility damaged by an explosion, is believed to have been made the day before by a KH-11 designated USA-224.

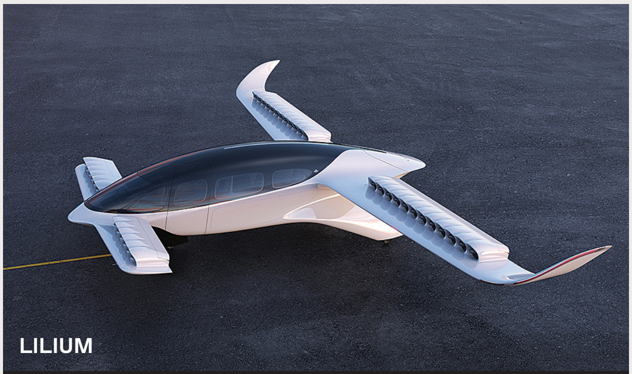
Will ordinary citizens ever get access to 10-cm resolution? Don't count on it. Superpower tensions are again sky-high, and even if they weren't, the U.S. government would still have a clear interest in keeping that capability to itself. Then, too, resolution probably won't improve much beyond 10 cm anytime soon: It depends on the size of a spy satellite's objective mirror, and that, in turn, is limited by the payload capabilities of the rocket that launches it. For orbiting big spooky satellites, the U.S. will soon transition from the Delta IV Heavy to a new rocket, the Vulcan. Its capabilities aren't much greater than the Delta IV's.

And, finally, if the world plunges into a new Cold War, its participants will leverage software, more so than hardware. The breakthroughs will be no less amazing. But they'll be even less visible than spy satellites. ■

GENE BLEVINS/REUTERS/ALAMY

News

Location United States **Funding** US $1.84 billion **Vehicle type** Vectored thrust **Aircraft status** Full scale **Range** 240 kilometers **Capacity** 5*



Location Germany **Funding** US $938 million **Vehicle type** Vectored thrust **Aircraft status** Tech demonstrator **Range** 250 kilometers **Capacity** 7*

Location United Kingdom **Funding** US $380 million **Vehicle type** Vectored thrust **Aircraft status** Scheduled for 2022 **Range** 160 kilometers **Capacity** 5*

Location Germany **Funding** US $376.6 million **Vehicle type** Multicopter **Aircraft status** Certification ready **Range** 35 kilometers **Capacity** 2*

SOURCE: SMG CONSULTING; ALL PHOTOS PROVIDED BY MANUFACTURERS

TRANSPORTATION

What's Behind the Air-Taxi Craze >

A wave of eVTOL startups aim to revolutionize transportation

BY EVAN ACKERMAN & GLENN ZORPETTE

When entrepreneur JoeBen Bevirt launched Joby Aviation 12 years ago, it was just one of a slew of offbeat tech projects at his Sproutwerx ranch in the Santa Cruz mountains, in California. Today, Joby has more than 1,000 employees and close to US $2 billion in funding.

Having raked in perhaps 30 percent of all the money invested in electrically powered vertical-takeoff-and-landing (eVTOL) aircraft so far, Joby is the colossus in an emerging class of startups working on radical, battery-powered commercial flyers. All told, at least 250 companies worldwide are angling to revolutionize transportation in and around cities with a new category of aviation, called urban air mobility or advanced air mobility. With Joby at the apex, the category's top seven companies

*Capacity may include a human pilot.

ARCHER AVIATION

Location United States **Funding** US $856.3 million **Vehicle type** Vectored thrust **Aircraft status** Tech demonstrator **Range** 100 kilometers **Capacity** 2*

BETA TECHNOLOGIES

Location United States **Funding** US $511 million **Vehicle type** Lift + cruise **Aircraft status** Full scale **Range** 460 kilometers **Capacity** 6*

EHANG

Location China **Funding** US $132 million **Vehicle type** Multicopter **Aircraft status** Certification ready **Range** 35 kilometers **Capacity** 2*

AIRBUS

Location France **Funding** Corporate **Vehicle type** Multicopter **Aircraft status** Tech demonstrator **Range** 80 kilometers **Capacity** 4*

KITTYHAWK

Location United States **Funding** Private **Vehicle type** Vectored thrust **Aircraft status** Tech demonstrator **Range** 160 kilometers **Capacity** 1*

WISK

Location United States **Funding** US $450 million **Vehicle type** Lift + cruise **Aircraft status** Full scale **Range** 40 kilometers **Capacity** 2* together have hauled in more than $5 billion in funding—a figure that doesn't include the private firms, whose finances haven't been disclosed.

But with some of these companies pledging to start commercial operations in 2024, there's no clear answer to a fundamental question: Are we on the verge of a stunning revolution in urban transportation, or are we witnessing, as aviation analyst Richard Aboulafia puts it, the "mother of all aerospace bubbles"?

Even by the standards of big-money tech investment, the vision of this future is giddily audacious. During rush hour, the skies over a large city, such as Dubai or Madrid or Los Angeles, would swarm with hundreds, and eventually thousands, of eVTOL "air taxis." Each would seat between one and perhaps half a dozen passengers, and would eventually be autonomous. Hailing a ride would be no more complicated than scheduling a trip on a ride-sharing app.

And somehow, the cost would be no greater, either. In a discussion hosted by the *Washington Post* last July, Bevirt declared, "Our initial price point would be comparable to the cost of a taxi or an Uber, but our target is to move quickly down to the cost of what it costs you to drive your own car."

Industry analysts tend to have more restrained expectations. Limited commercial flights will probably begin a year or two from now, and with the exception of China, all aircraft will be flown by pilots for at least the next six to eight years. (As detailed below, at least one Chinese company has already flown autonomous trials.) Costs are expected to be similar to those of helicopter trips, which tend to be in the range of $6 to $10 per mile or more. Of the 250+ startups in the field, only three—Kittyhawk, Wisk (a joint venture of Kittyhawk and Boeing), and Ehang—plan to go straight to full autonomy without a preliminary phase involving pilots, says Chris Anderson, chief operating officer at Kittyhawk.

To some, the autonomy issue is at the heart of whether this entire enterprise can succeed economically. "When you figure in autonomy, you go from $3 a mile to 50 cents a mile," says Anderson, citing studies done by his company. You can't do that with a pilot in the seat."

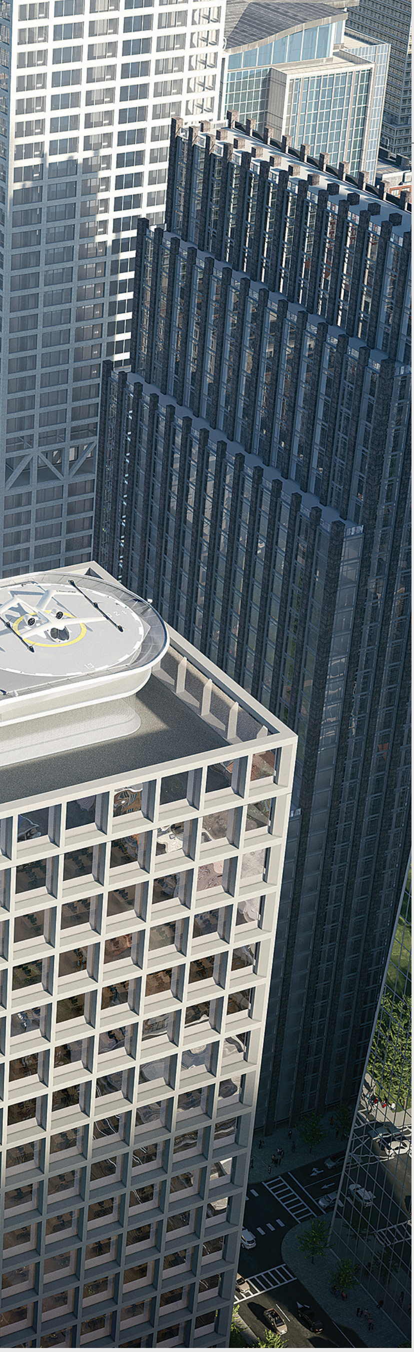
Georgia Tech professor Laurie A. Garrow agrees. "For the large-scale vision, autonomy will be critical," she says. Garrow, a civil engineer who codirects the university's Center for Urban and Regional Air Mobility, adds that autonomy presents challenges beyond technology: "We're going to have to get the consumer used to thinking about flying in a small aircraft without a pilot on board. I have reservations about the general public's willingness to accept that vision, especially early on."

Some analysts have much more fundamental doubts. Aboulafia, managing director at the consultancy AeroDynamic Advisory, says the figures simply don't add up. EVTOL startups are counting on mass-manufacturing techniques to reduce the costs of these exotic aircraft, but such techniques have never been applied to produce aircraft on the scale specified in the projections. Even the anticipated lower operating costs, Aboulafia adds, won't compensate. "If I started a car service here in Washington, D.C., using Rolls Royces, you'd think I was out of my mind, right?" he asks. "But if I put batteries in those Rolls Royces, would you think I was any less crazy?"

What everyone agrees on is that achieving even a modest amount of success for eVTOLs will require surmounting entire categories of challenges. At the

The "pinch point" in many forecasts involving eVTOL aircraft is expected to center around the sites where the eVTOLs take off and land—the so-called vertiports.

VOLOCOPTER



top of that list: certification. "The technical problems are, if not solved, then solvable," says Anderson. "The main limiters are laws and regulations."

Consider the Federal Aviation Administration, the certifying body in the United States. To clear an aircraft for commercial flight, the FAA requires three certifications: one for the aircraft itself, one for its operations, and one for its manufacturing. For eVTOLs (other than multicopters), the applicable category seems to be Title 14 Code of Federal Regulations, Part 23, which covers "normal, utility, acrobatic, and commuter category airplanes." The certification process itself is performance based, meaning that the FAA establishes performance criteria that an aircraft must meet, but does not specify how it must meet them.

Nobody knows how many eVTOL startups have started the certification process with the FAA, although a good guess seems to be one or two dozen. Joby is furthest along in the process, according to Mark Moore, CEO of Whisper Aero, a maker of advanced electric-propulsor systems in Crossville, Tenn. The certification proposals submitted by the companies for their aircraft are not public, but when one (presumably Joby's) is accepted by the FAA, it will become available through the U.S. Federal Register. Observers expect that to happen any day now.

This certification phase of piloted aircraft is fraught with unknowns because of the novelty of the eVTOL craft themselves. But experts say a greater challenge lies ahead, when manufacturers seek to certify the vehicles for autonomous flight. "If very high levels of automation are critical to scaling, that will be very difficult to certify," says Matt Metcalfe, a managing director in Deloitte Consulting's future of mobility and aviation practice.

"It's a matter of, how do you ensure that that autonomous technology is going to be as safe as a pilot?" says an official with one of the eVTOL startups. "How do you certify that it's always going to be able to do what it says? With true autonomous technology, the system itself can make an undetermined number of decisions, within its programming. And the way the current certification regulations work, is that they want to be able to know the inputs and outcome of every decision that the aircraft system makes. With a fully autonomous system, you can't do that."

Perhaps surprisingly, most experts contacted for this story agreed with Kittyhawk's Anderson that the technical challenges of building the aircraft themselves are solvable. Even autonomy—certification challenges aside—is within reach, most say. For example, the Chinese company EHang has already offered commercial autonomous flights of its EH216 multicopter to tourists in the northeastern port city of Yantai.

A more imposing challenge, and one likely to determine whether the grand vision of urban air mobility comes to pass, is whether municipal and aviation authorities can solve the challenges of integrating large numbers of eVTOLs into the airspace over major cities. Some of these challenges are, like the aircraft themselves, totally new. For example, most viable scenarios require the construction of "vertiports" in and around cities. These would be like mini airports where the eVTOLs would fly in and out and be recharged.

According to Garrow, vertiports will be the "pinch points," because at urban facilities, space will likely be limited to accommodating several aircraft at most. And yet at such a facility, room will be needed during rush hours to handle dozens of aircraft.

Despite all the challenges, Garrow, Metcalfe, and others are cautiously optimistic that air mobility will eventually become part of the urban fabric in many cities. That's not to say, though, that the vision of middle-class people being routinely whisked around cities for a few nickels and dimes per mile is a sure thing. But if it does happen, a few studies have predicted that travel times and greenhouse-gas and pollutant emissions could all be reduced.

A 2020 study published by the journal *Transportation Research Record* found a substantial reduction in overall energy use for transportation under "optimistic" scenarios for urban air mobility. And a 2021 study by researchers at the University of California, Berkeley and the NASA Ames Research Center found that in the San Francisco Bay Area, overall travel times could be reduced with as few as 10 vertiports. The benefits went up as the number of vertiports increased and as the transfer times at the vertiports went down.

Metcalfe notes that ubiquitous modern conveniences such as online shopping have already unleashed tech-based revolutions on a par with the grand vision for urban air mobility. Imagine time-traveling back to the founding of Amazon.com in 1994. Could anyone have predicted the complete upending of the consumer economy that this one company would bring about? "We never would have thought we'd be getting two or three packages a day," Metcalfe points out. "Similarly, the way we move people and goods in the future could be very, very different from the way we do it today." ■

CONSUMER ELECTRONICS

Your Digital Trash Is a Cybercrook's Treasure > Data can be the diamond discovered in a dumpster dive

BY JULIANNE PEPITONE

Many of us have obsolete devices relegated to the backs of our drawers, little museums of the technology of days long past. These forgotten laptops and phones seem like merely quaint relics, but if they're not disposed of correctly, they can leak two different but dangerous things: toxic chemicals and sensitive data.

The world generated a record 53.6 million tonnes of electronic waste in 2019, up more than 21 percent over five years, according to the United Nations' most recent assessment.

Only about 17 percent of that e-waste was recycled, and what happens to the rest can be detrimental for both human health and privacy. A new systematic review by the *Lancet* found that "people living in e-waste exposed regions had significantly elevated levels of heavy metals and persistent organic pollutants," and it advocated for "novel cost-effective methods for safe recycling operations… to ensure the health and safety of vulnerable populations."

John Shegerian couldn't agree more. He's the cofounder and CEO of ERI, one of the largest electronics recycling-and-disposal providers in the world, and the coauthor of ERI's 2021 book *The Insecurity of Everything: How Hardware Data Security Became the Biggest Issue Facing the World Today.*

We spoke with Shegerian about e-waste's effect on the future of our world and our privacy, and the role engineers can play in solutions. The conversation has been edited for length and clarity.

The conclusion of the *Lancet* study surely isn't a shock to you, but others might be surprised about the kinds of pollutants inside our old computers, phones, and TVs—and the danger they present when not handled responsibly.

John Shegerian: When we got into the industry [in 2002], Al Gore had not yet won his awards for *An Inconvenient Truth.* There was no iPhone or Internet of Things. But [e-waste] was still already the fastest-growing solid-waste stream in the world. Now, in 2022, electronic waste is the fastest-growing waste stream by an order of magnitude.

The magnitude of the problem grossly outstrips the amount of solutions. We have so, so, so many devices. And when [e-waste isn't disposed of correctly], it can get put into a landfill, thrown into a river or a lake, or just buried. Sadly, it could also be sent to a country where they don't have the right tools or expertise to dismantle old electronics.

Eventually the linings [of devices] break, and when they're rained upon, the very toxic materials [they contain]—mercury, lead, arsenic, beryllium, cadmium—come out. If they get back into the land and water, it has very negative effects on the health of our vegetation, our animals, and our people. So, unfortunately, no, I'm not surprised [by the *Lancet* study].

You founded ERI because of the environmental concern, but you and your team quickly came to realize the cybersecurity risk as well: Many of these tossed-out devices contain sensitive personal or professional data.

J.S.: Yes, we saw these little breadcrumbs about data and privacy throughout the 2000s: the birth of Palantir [Technologies], the founding of LifeLock, and what we were seeing ourselves at ERI. Really, in 2012, I started speaking to companies about the need to "shred" data the way they shred sensitive papers. They looked at us like we were green Martians. Over the years, I spoke about it at conferences anyway, and at one of these in 2017, Robert Hackett from *Fortune* asked for an interview and wrote an article that ended with this line: "Turns out e-waste isn't just an environmental menace, but a cybersecurity one too." Five years of banging the drum, and thanks to this article, we were finally off to the races…comparatively.

Comparatively. Because you find that people, both as individuals and on the enterprise level, aren't taking the data risk seriously enough. How did that inspire *The Insecurity of Everything*?

J.S.: Technology is so ubiquitous that this is a societal problem we all have to reckon with. It's much more serious than just affecting your family or your company. This is a problem of international magnitude, that has homeland-security risks around it. That's why we wrote the book: The vast majority of our clients still were not listening. They just wanted us for environmental work, but they weren't really sold on the hardware data-destruc-

GETTY IMAGES

tion part of the work yet. We wanted to write this book to share some examples of serious consequences—that this isn't some remote, theoretical concern.

Can you share some of those anecdotes?

J.S.: I once had a big, big bank call me up: "John, we've had a breach, but we don't believe it's phishing or software. We think it came from hardware." I go out there, and it turns out one of their bankers threw his laptop in the trash in Manhattan and someone fished it out. On that laptop was information from the many clients of the entire banking firm—and the bank's multibillion-dollar enterprise. The liability, the data...God, just absolutely priceless. If it got into the wrong people's hands, the ransom that could have been extracted was truly of huge magnitude.

You also have situations like the federal government—I won't say what branches—telling us: "We have all of these old electronics that are potentially data-heavy, and when companies like yours gave us quotes [for responsible recycling], it seemed kind of expensive. We were told to save money and we found someone to do it for free."

Free? Yeah, no. What happens is that a guy will pick up the devices for free, put them in a container, and sell them wholesale to the highest bidder. Lots of those buyers are harvesting the precious metals and materials out of old electronics—but there are also people adverse for homeland security who want to pull out the hard drives and find a way to harm us here in the United States or hold corporate data for ransom. From those examples you can see how you need to protect your financial and personal data on an individual level too.

What do people need to know—and do—to avoid becoming one of these stories?

J.S.: It is crucial to make sure that if you're giving [your device] to a retailer who has a take-back or trade-in program, vet them and make sure they're using responsible recyclers. Make sure they guarantee you that all your data will be destroyed before they take your phone and resell it. If they won't tell you, with radical transparency, who the vendor is handling the materials or where they're going to go? Pass.

For the engineers of today and tomorrow who are interested in this work, how can they be part of the solution?

J.S.: Engineers have been such important partners for us, whether it's creating e-waste shredding machines or things like glass-cleaning technology that helps us recycle materials. They've also helped us be the first to develop AI and robotics in our facility. So, they could come to work for someone like us and answer questions like: How do we recycle more of this material in a faster and better way, with less impact to the environment?

On the other side, engineers are still going to be hired by great original equipment manufacturers, whether tech or auto companies, and that's beautiful because now they could design and engineer for circular economy behavior. They could create new products made of recycled copper, gold, silver, steel, plastics—keeping them out of our landfills.

Engineers have a huge opportunity to help leave the world a better, safer, and cleaner place than we inherited. But everyone on Earth is a stakeholder in this. We all have to be part of the solution. ■

COMPUTING

Novel Sonic Transistors: The Shape of Tomorrow's Electronics?

> Topological acoustic transistor points the way to dissipationless electronic circuits

BY CHARLES Q. CHOI

Potential future transistors that consume far less energy than today's devices may rely on exotic materials called topological insulators, in which electricity flows across only surfaces and edges, with virtually no dissipation of energy. In research that may help pave the way for such electronic topological transistors, scientists at Harvard have now invented and simulated the first acoustic topological transistors, which operate with sound waves instead of electrons.

Topology is the branch of mathematics that explores the nature of shapes independent of deformation. For instance, an object shaped like a doughnut can be deformed into the shape of a mug, so that the doughnut's hole becomes the hole in the cup's handle. However, the object couldn't lose the hole without changing into a fundamentally different shape.

Employing insights from topology, researchers developed the first electronic topological insulators in 2007. Electrons

HOFFMAN LAB/HARVARD SEAS

Topological transistors could someday be the key component of computers that consume much less energy and generate a lot less heat. The type shown here conducts sound waves instead of electricity.

zipping along the edges or surfaces of these materials are "topologically protected," meaning that the patterns in which the electrons flow stay unchanged in the face of any disturbances they might encounter—a discovery for which these innovators were awarded the Nobel Prize in Physics in 2016. Scientists later designed photonic topological insulators, in which light is similarly protected.

However, creating electronic topological transistors in which the dissipationless flow of electrons can get switched on and off in topological materials requires dealing with complicated quantum mechanics. By using sound instead of charge, the Harvard scientists were able to sidestep this complexity to create acoustic topological transistors.

Still, designing an acoustic topological transistor wasn't easy. "We knew our approach to topological logic could work, but we still needed to find a viable selection of materials where it actually did work," says study lead author Harris Pirie, currently at the University of Oxford. "We took a fairly brute force approach: There was one summer where we were running calculations on about 20 computers at the same time to test thousands of different materials and designs."

The design the Harvard researchers settled on consists of a honeycomb lattice of steel pillars anchored to a plate made of another substance, all sealed in an airtight box. The plate is made of a material that expands greatly when heated.

The steel lattice has slightly larger pillars toward one end and slightly smaller ones toward the other. These differences in the size and spacing of the pillars govern the lattice's topology, which in turn influences whether sound waves can flow through a particular subset of pillars or not. For instance, at 20 °C, ultrasound cannot pass through the device, but at 90 °C, it can zip unimpeded along the device's edges. In essence, heat can switch this device from one state to another, much as electricity does with conventional transistors.

The researchers noted that these acoustic topological transistors are scalable. This means the same design could also work for the gigahertz frequencies commonly employed in circuitry that is potentially useful for processing quantum information, Pirie says.

"More generally, the control of topologically protected acoustic transport has applications in a number of important fields, including efficient acoustic-noise reduction, one-way acoustic propagation, ultrasound imaging, echolocation, acoustic cloaking, and acoustic communications," he says.

The design principles used to develop acoustic topological transistors could be adapted for use in photonic devices in a fairly straightforward manner, "at least in principle, because the acoustic wave equation mathematically maps onto its photonic counterpart," Pirie says. Meaning: The physics of sound waves and light waves are similar enough that the lessons of a topological transistor of one variety easily translate to a topological transistor of the other kind.

However, Pirie says, "this mapping doesn't exist in electronics," which makes it more challenging to develop an electronic topological transistor from this work. "It's still likely we could follow the same general scheme in electronics—we just have to find the right materials to use," he notes.

The scientists detailed their findings online earlier this month in the journal *Physical Review Letters*. ■

JOURNAL WATCH

Can Autonomous Cars Show Pedestrians Their Intentions?

Judging whether it's safe to cross the open road involves a complex exchange of social cues between pedestrian and driver. But what if there's no one behind the wheel? Autonomous-vehicle company Motional thinks that making the vehicles more expressive could be the key to maintaining those crucial signals.

When he's waiting at a crosswalk, Paul Schmitt, chief engineer at Motional, engages in what he calls the "glance dance"—a rapid and almost subconscious assessment of where oncoming drivers are looking and whether they're aware of him. "With automated vehicles, half of that interaction no longer exists," says Schmitt. "So what cues are then available for the pedestrian to understand the vehicles' intentions?"

To answer that question, his team hired animation studio CHRLX to create a highly realistic virtual-reality experience designed to test pedestrian reactions to a variety of different signaling schemes. Reporting their results in *IEEE Robotics and Automation Letters*, Schmitt and his team showed that exaggerating the car's motions—by braking earlier or stopping well short of the pedestrian—was the most effective way to communicate its intentions.

The company is now in the process of integrating the most promising expressive behaviors into its motion-planning systems, and it has also open-sourced the VR traffic environment so that other groups can experiment.

The study tested various expressive behaviors meant to implicitly signal to pedestrians that the car was stopping for them. These included having the car brake earlier and harder than the baseline, stopping the car a vehicle's length away, adding exaggerated braking and low-revving sounds, and finally combining these sounds with an exaggerated dipping of the nose of the car, as if it were braking hard.

The team measured how quickly the participants decided to cross the roadway, and also gave them a quick survey after each trial to find out how safe they felt, how confident they were of their decision to cross, and how clearly they understood the car's intention. The car stopping short elicited the highest ratings for sense of safety and intention understanding.

The fact that stopping short elicited the best response isn't surprising, says Schmitt, as this approach was inspired by the way human drivers behave when slowing down for pedestrians. What was surprising, he adds, was that there was little difference between the reactions to the baseline scenarios with and without a driver, which suggests pedestrians are paying more attention to the movement of the vehicle than to the driver behind the wheel. —Edd Gent

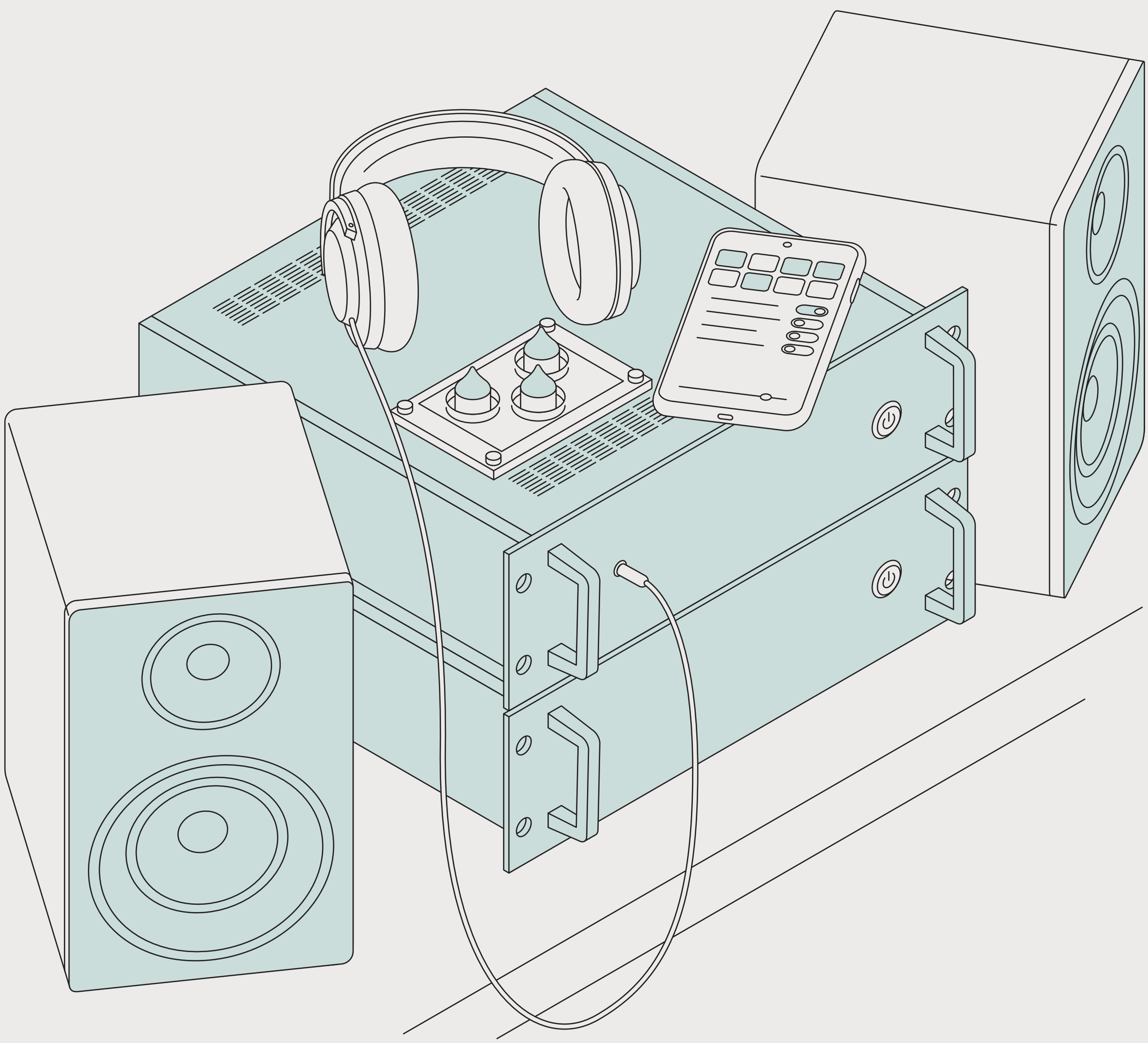
Electric Buses Take Charge

By Willie D. Jones

Pictured is the factory where electric-vehicle maker BYD, based in Santa Dominguez, Calif., builds its rechargeable transit and charter buses. BYD says it owes its preeminence in the electric-bus market to the fact that its buses' iron-phosphate batteries can be topped off through the AC or DC plugin ports, via overhead catenaries, or from inductive chargers embedded in road surfaces. Among the buses BYD is turning out is the Type J6, which can travel more than 140 kilometers on a single charge. Last year, four of them were put into service in Japan's first-ever all-electric public-transit loop, in Kyoto. The 29-seater bus is also designed to serve as a mobile emergency power source that can plug into the grid during outages.

PHOTOGRAPH BY CHRISTOPHER PAYNE/ESTO

Hands On

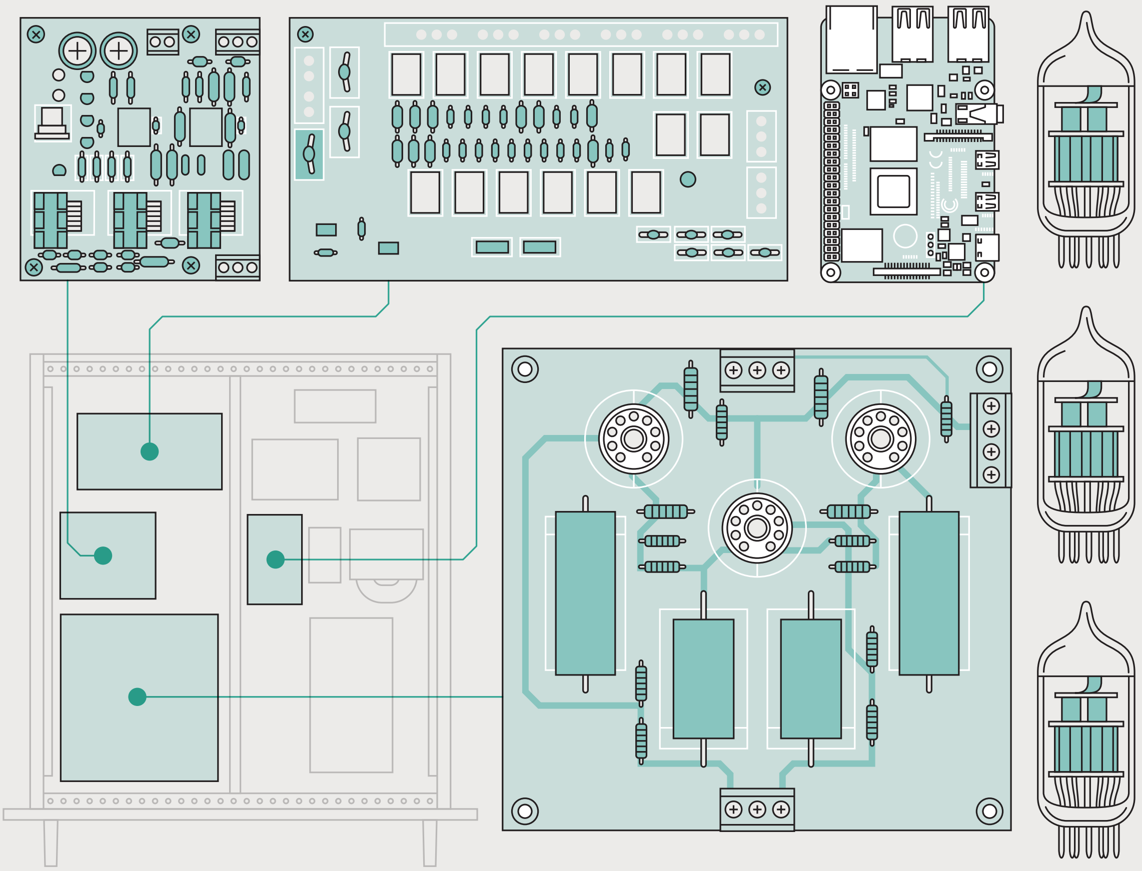


A Next-Gen DIY Audio Amp › A Web-enabled integrated amp that won't break the bank

BY MATTHEW PAULSON

For a long time, I owned a beloved Sansui Electric integrated amplifier. These audio amplifiers combine a preamplifier for boosting the sound signal and a power amplifier for driving the loudspeakers. Sansui went out of business several years ago, and, although old units can still be found, when my amplifier finally died a crackly death, I decided it was time to consider something modern and more flexible. And I'd already built my own speakers, so why not build it myself?

Illustrations by James Provost

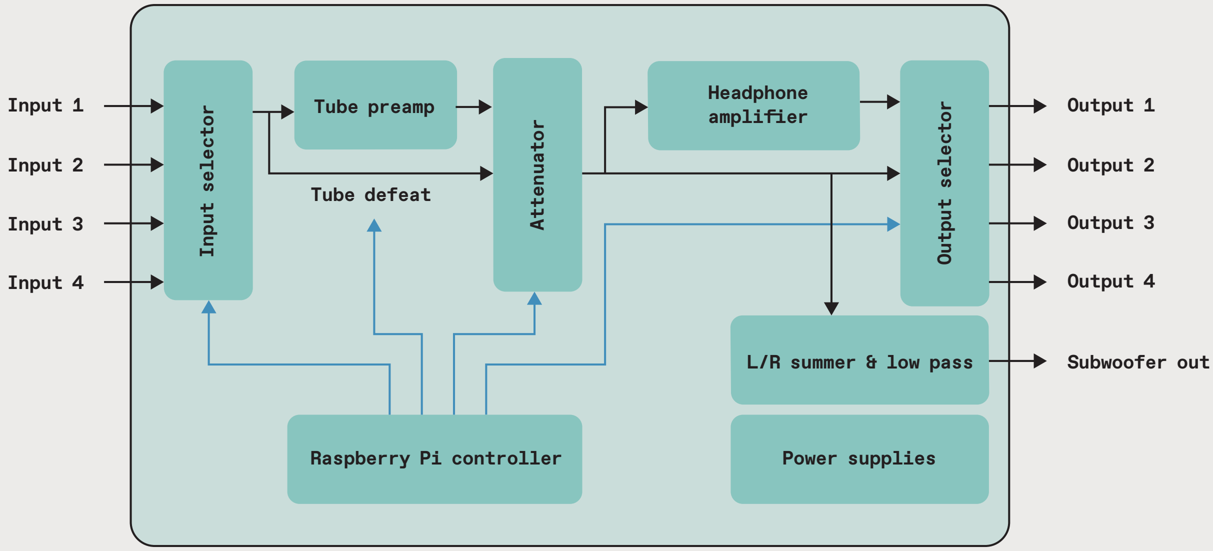


My preamplifier uses a combination of custom and off-the-shelf components, including a wireless-enabled Raspberry Pi [top right] and a Zerozone amplifier [bottom right] that uses three tubes [far right]. The headphone amplifier and digital attenuator I made myself [top left, top middle]. The remaining components are power supplies.

Researching homebrew audio sites, I came across Glenn Zorpette's November 2018 Hands On article, "DIY Pro Audio," in *IEEE Spectrum*, and it convinced me it was possible, although I wanted to go beyond just a power amplifier to something more like my lamented Sansui. I also wanted to add volume and input/output controls. And a headphone amp. And use tubes, oh my!

So consider this a spiritual successor to Zorpette's 2018 amplifier. The first thing I tackled was the volume control. I wanted to use a relay-based volume control that controls the volume in discrete steps to eliminate the noise that can accompany traditional analog volume controls. I scoured eBay for relay-based controls but realized that they still have potentiometers: An analog-to-digital converter reads the voltage coming out of the pot and energizes the corresponding relays—even a new pot could be noisy.

So I decided to drive my own relays digitally and control them via a Web interface. No knobs or switches to wear out! I located a similar project by Jos van Eijndhoven online and decided to use his approach of employing a ladder of attenuating resistors, which would give me 64 distinct volume steps without introducing audible distortion. To this board I also connected a tap along with a low-pass filter and output—just in case I decide to build my own subwoofer speaker! I picked a Raspberry Pi 4 with 4 gigabytes of memory as my controller. In commercial product development, an optimized microcontroller would be the way to go, but for my DIY project, a Pi was perfect. It has lots of input/output pins for hardware interfacing, and it's easy to develop on. My final design needed only 300 lines of Python code (including the Web server), and 500 lines of HTML/JavaScript. I was able to make a professional-looking Web interface by



Using a Web interface running on the Raspberry Pi controller, inputs and output can be selected, the tube amplifier bypassed using a "defeat" option, and one of 64 volume levels selected by the attenuator. The output from the attenuator passes into a headphone amplifier, output selector, and a low-frequency subwoofer output.

using g200kg's webaudio-control library of graphical user-interface widgets.

For preamplification, I've always loved the sound of tubes. After some reading, I settled on buying a Zerozone design based on three 12AU7 tubes (which are still being manufactured today). I chose a 12AU7-based design because of the tube's smooth sound. I also added a "defeat" or bypass option for A/B comparisons that let me disable the preamp stage—with this activated, the design is 100 percent passive. I also skipped tone control in the name of providing as pure a path for the audio as possible.

For my headphone amplifier, I initially tried a so-called John Linsley Hood class-A design from the 1970s (usually referred to as a JLH class-A). But it was hissy and ran hot. I had no interest in fiddling with low-noise transistors or modifying the circuit to use MOSFET transistors to solve this problem, so I looked around again. I found the Pimeta v2 schematics for a portable amplifier, which met most of my needs, although I had to tweak the design to fit my power supply.

In fact, the power supply was my biggest headache because of the number and range of voltages needed in a digitally controlled audio amplifier that's using tubes. I needed ± 200 volts, 24 V, ± 12 V and 5 V. Trust me: there is no single power supply on eBay that will do this. I could have designed my own, but I had little experience with high-voltage tube supplies. In the end I used multiple commercial supplies.

For the final power-amplifier stage, I settled on a $250 SDS-250 Power Amplifier Kit from Class D Audio and put it into a second cabinet identical to the case holding my preamp. This was an easy build and sounds quite nice to my ears, and although the cabinet is really too large for the power amp, I like the way it looks stacked below the preamp.

Integrating all the commercial assemblies with my own relay and headphone amp boards required a few revisions, and I developed the control software in parallel. I used a function generator to inject a signal at various points to trace out problems (I also had to do some reading about grounding strategies to reduce 60-hertz hum from my AC mains supply).

Packaging was straightforward if not tedious. I used a plexiglass substrate to mount the components on the inside of the cabinet. It's easy to machine with woodworking tools, and a great choice if you don't have access to fabrication tools. The tubes run quite cool in a large cabinet such as the one I selected, so there's actually no need to have them poke through the top. But the rule of cool dictated that I make them do just that!

I do have a few minor issues, such as an occasional click when passing the volume through the 50 percent mark, depending on the music. I might be able to mitigate this with a software change, but additional resistor ladder stages are a better idea. Other future goals include adding a tone control and designing a smaller, simpler power supply. But one thing is clear—you can still build a great-sounding amplifier relatively inexpensively, and now with even more cool features, and dare I say, *style*! ■

The power supply was my biggest headache because of the number and range of voltages needed.

Careers

Stefany Allaire › A micromanufacturer carves her niche

STEPHEN CASS

STEFANY ALLAIRE

It's a tough time in electronics manufacturing, especially for small outfits. The Great Semiconductor Shortage is driving up the cost of components—if they can be found at all. But Stefany Allaire has not been deterred, delivering products and developing new ones for her dedicated community of customers. Allaire runs Feonix Retro Systems, which caters to the "new retro" market, an emerging niche in retrocomputing that involves going beyond restoring, modding, or replicating old computers. New-retro machines remix old technologies with the modern, creating original systems that strive to retain the essential characteristics of classic computers, such as simplicity and transparency.

For Allaire, it's a return to the technologies that started her career. "I was 11 or 12, and our dad bought a Commodore 64.... I got interested in hacking games at first. After that, I started doing more hardware stuff." Allaire went on to do staff and freelance design work for a number of companies, specializing in field-programmable gate arrays (FPGAs) and electronic hardware design.

From 2008 to 2013 she lived in Los Angeles, designing equipment for the movie industry, and pioneering global shutter sensor cameras. (Global shutters eliminate motion and flicker artifacts that occur with traditional rolling shutters, which build up an image by scanning sequential rows over time.) She also tried to break into moviemaking, but ran afoul of Hollywood's brutal competition. "I came out of there a little bit with my tail between my legs.... I had to leave my car there because I couldn't pay for it."

Allaire rebounded doing contract engineering for Huawei. But after her return home to Canada,"I was kind of bored, and I started doing a little bit of retro," says Allaire. Then in 2018 she came across a video from David Murray, also known as the 8-Bit Guy, where he described his dream new-retro computer. "I thought, 'This is perfect timing. I'll accept the challenge.' I started doing the design out of his requirements," After some initial collaboration with Murray however, Allaire realized that she was interested in much higher-end systems than he had in mind, and they parted ways: "I often say that I'm kind of the Silicon Graphics of the new-retro computer wave," laughs Allaire. She worked various day jobs, founding Foenix Retro Systems as a sideline until deciding to take it on full-time last year.

Allaire's sales are too low-volume for her to farm out manufacturing. "Everything is built by hand," says Allaire. She has learned to order as many parts as possible as soon as she sees they are available. "I've experienced where parts were in stock, and I bought just a couple. And then the next day all the rest were gone."

Allaire's machines pair a classic CPU like the 8/16-bit 65C816 or the 16/32-bit Motorola 68000 with an FPGA that provides colorful 2D graphics and emulates classic sound chips. Her latest product, the A2560K, also features an integrated keyboard like the home computers of the 1980s. They appeal to the kind of person who is not afraid of programming in assembly, enjoys electronic music, and likes old-school games.

Allaire keeps in close contact with this target group through her Discord channel, where she encourages people to write software and provides frequent progress updates. She also manages expectations when manufacturing issues cause delays. This leads to the core of her advice for anyone thinking of starting a company. "You need to be worried about your customer. You need to take care of your customer," says Allaire. It's an approach that appears to have paid off in loyalty: "90 percent of my customers are repeat customers," she says. ■

Crosstalk

Africa's Access to Electricity

In an era of plenty, one continent still lags

We measure access to electricity no better than we do the rate of literacy. Both are easy to define—a population's share connected to the national grid or to a local source of electricity, and the ability to read and write—but such definitions do not make it possible to get a truly informed verdict. There is an enormous difference between the hesitant reading of a simple text and the comprehension of classics in any language, and between filling out vital information on a short questionnaire and writing lengthy polemic essays.

Similarly, having a distribution line running to a dwelling (perhaps without the utility's consent) tells us nothing about the usage of power or the reliability of its supply. Knowing how many solar panels are on a roof informs us about the maximum possible rate of local generation but not about the annual capacity factor or about the final uses of generated electricity. Therefore, to understand the progress of electrification, we need to augment the rate of nationwide access with information on the urban-rural divide and on actual per capita consumption.

Global electrification has risen steadily since World War II, reaching 73 percent in 2000 and 90 percent in 2019 (the pandemic year of 2020 was the first year in decades when the rate did not go up). This means that in 2019 about 770 million people had no electricity, three-quarters of them in Africa.

Nighttime satellite images show that the heart of the continent remains in darkness: Electrification rates are less than 10 percent in Chad, the Central African Republic, and the Democratic Republic of the Congo, and the rates remain below 50 percent in such populous countries as Angola, Ethiopia, Mozambique, and Sudan. Even South Africa, by far the best-supplied country south of the Sahara, suffers from frequent blackouts.

Real access to electricity in large parts of Africa is akin to where the United States was during the late 1890s.

The urban-rural divide has been eliminated in North Africa's Arab countries, but it remains wide in sub-Saharan Africa, where 78 percent of urban populations but only 28 percent of rural inhabitants have connections. Even countries that have seen recent economic progress have the problem—the urban to rural breakdown is 71 to 32 percent in Uganda and 92 to 24 percent in Togo.

For purposes of comparison with rates in affluent countries, I will leave out the top per capita consumers (from Iceland's 50,000 kilowatt-hours per year to Canada's 14,000 kWh/year). Instead, I will use the rate of 6,000 kWh/year, which is the unweighted mean for the European Union's four largest economies—Germany, France, Italy, Spain—and Japan.

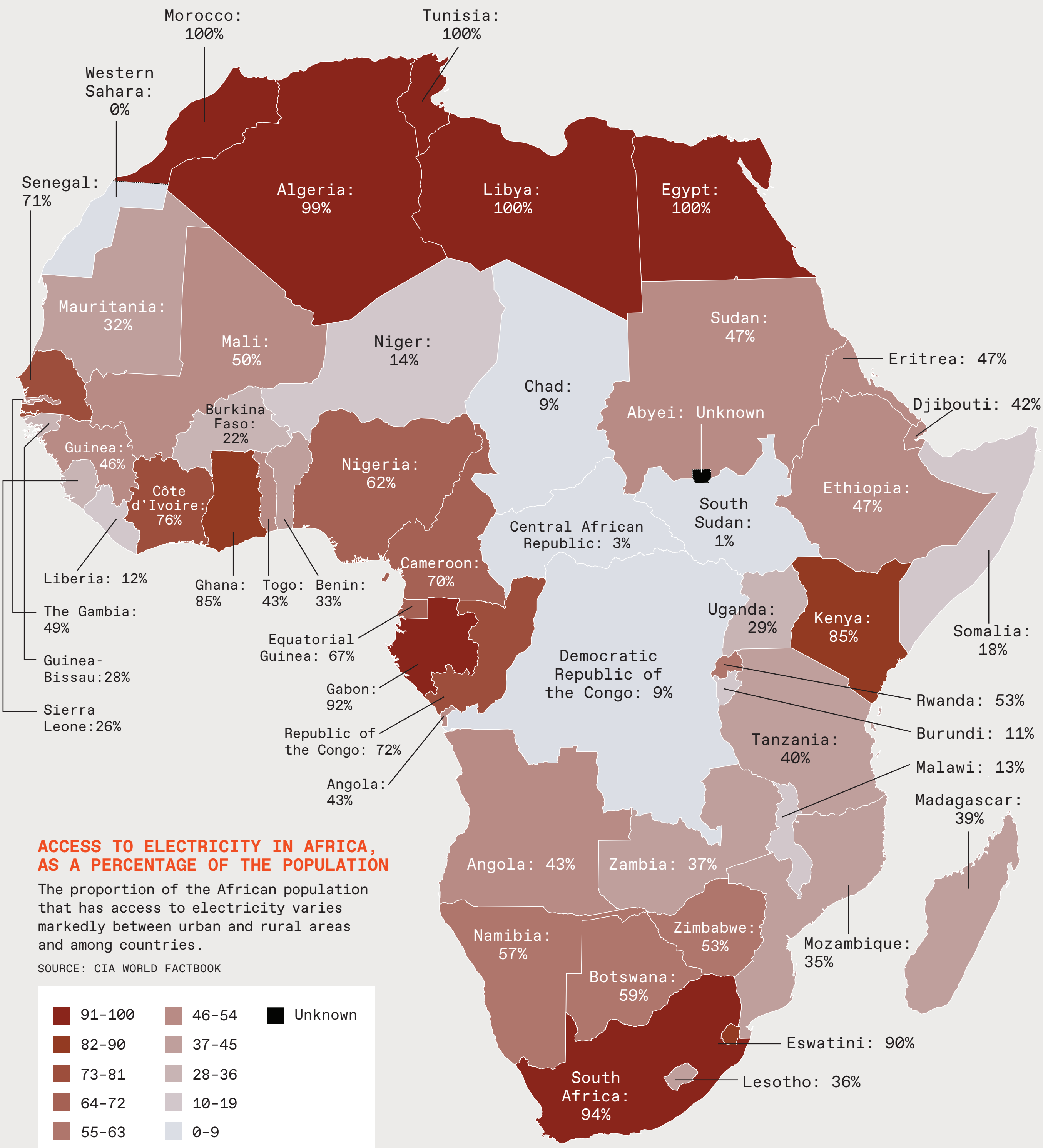
Only North Africa has consumption rates of the same order of magnitude. Egypt, for instance, is at about 1,500 kWh/year, or a quarter of the affluent rate. Nigeria's rate (about 115 kWh) is an order of magnitude lower and there are many countries (Burundi, Central African Republic, Chad, Ethiopia, Guinea, Niger, Somalia, South Sudan) where the mean is below or just around 50 kWh/year, or less than 1 percent of the affluent rate.

What does 50 kWh/year deliver? A 60-watt light switched on for a little over 2 hours a day—or one 60-W light, a small TV (25 W), and a small table fan (30 W) concurrently on for about an hour and 10 minutes. All too obviously, real access to electricity in large parts of Africa is akin to where the United States was during the late 1890s. ■

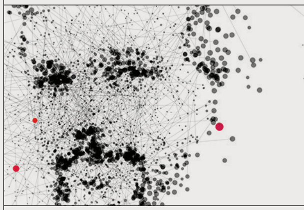
ACCESS TO ELECTRICITY IN AFRICA, AS A PERCENTAGE OF THE POPULATION

The proportion of the African population that has access to electricity varies markedly between urban and rural areas and among countries.

SOURCE: CIA WORLD FACTBOOK



 BY MATTHEW S. SMITH



A Laptop That's Fit to be Fixed

Dell's concept responds to the "right to repair" movement

DELL TECHNOLOGIES

In December 2021, just before CES, the world's leading tech event, Dell introduced the Concept Luna, a reimagining of the laptop that focuses on repairability.

Modern laptops are notoriously hard (and sometimes impossible) to repair, a problem Luna's designers address by reducing the number of screws to four and avoiding permanent adhesives. Instead, many parts lock into place. Dell has set itself the goal of reusing or recycling one equivalent product for every product it sells. Luna, a laptop that can be disassembled and repurposed, could help achieve that goal.

Repairability dovetails with the larger goal of sustainability. Luna looks like Dell's latest XPS 13, but clever tweaks have slimmed its carbon footprint. It's designed for on-demand production to reduce waste from unsold inventory. The motherboard, among the most resource-intensive components, is shaved to a quarter of its typical size. The stamped aluminum is designed to minimize scrap and may be recycled at the laptop's end of life.

Dell isn't alone in its focus on sustainability. LG announced at CES 2022 that its new OLED TVs will use more recyclable materials and cut packaging waste, and Lenovo introduced a Yoga laptop partially made of recycled plastics. These steps follow a trend set by Apple, which uses recycled aluminum in several devices including the MacBook Air and iPad.

These efforts strike a chord with the public. Among people in advanced economies, 72 percent are concerned that global climate change will harm them, according to a Pew survey. Only 46 percent had confidence in efforts to reduce the effects of global climate change. And climate change isn't the only problem worth worrying about. Consumer electronics can cause deadly pollution by degrading into hazardous materials (including lead, mercury, and arsenic) when left in landfills.

Modern electronics often remain relevant for at least five years; routers, displays, and high-end computers can be useful for a decade or more.

Sustainable, repairable devices may help consumers feel they're contributing less to these long-term problems, but there's also an immediate advantage: lifespan. Modern electronics often remain relevant for at least five years; routers, displays, and high-end computers can be useful for a decade or more.

Unfortunately, a device's life is often cut short by a problem that should be (but isn't) repairable. Luna would let users replace or upgrade components after purchasing. A stuck key or bulging battery would no longer be a death sentence.

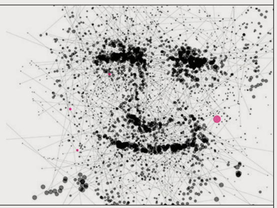
Framework, a startup that released its first laptop in 2021, is already putting this idea into practice. The company's namesake laptop is designed for easy access to its internal hardware. Owners can replace the hard drive, battery, or Wi-Fi adapter, and expansion cards let owners replace or swap ports. Framework's laptop is not as compact or modular as Dell's concept, but you can buy it right now.

Apple, too, is preparing a Self Service Repair program that will sell parts for iPhones, iPads, and Macs directly to consumers. Owners will be able to fix their devices with new, official repair manuals.

In the case of iPhone and iPad, these will be the first official repair manuals ever released.

The cynic in me must point out that these steps are insignificant next to the global change needed to stop the progress of climate change. Repairing the screen in an iPhone will not halt a heat dome.

Still, progress should not be overlooked. Consumer electronics won't change overnight, but that doesn't mean change is impossible. It's important that Dell, and others in consumer electronics, know we want sustainable materials, modular design, and devices we can fix and keep using for years. These changes are just small steps in the marathon effort to curb climate change, but they take us in the right direction, all the same. ■



Building Boom

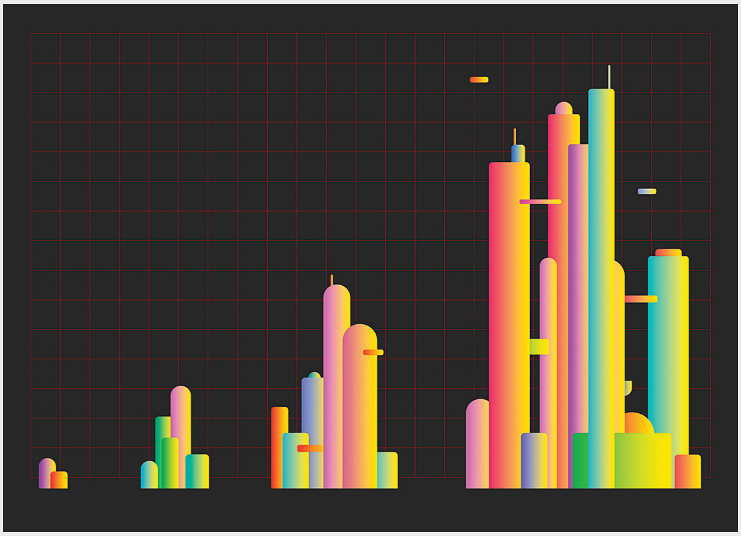
Population growth and climate change have an upside

For the rest of this century, humankind will be building cities at an unprecedented pace. World population is projected to increase from 7.9 billion to more than 10 billion, and much of that increase will occur in parts of the world that lag in infrastructure. Everywhere, people will expect to catch up, and then surpass. China is an example of how this can happen in just 30 years.

But there are two other factors that will supercharge the building boom. A large proportion of the people who now live in rural areas will move to cities. That will not only swell the populations of existing cities, it will also create new ones. Concurrently, rising sea levels caused by climate change will swamp many coastal cities, forcing them to rebuild parts of themselves on higher ground. Cities including Boston and New York are already spending substantial sums on projects to hold back the sea, which has begun encroaching in subways and road tunnels. But that is just a small precursor of what will come.

One problem with our current building methods is that they have a high carbon footprint, meaning that the act of building will increase the need for yet more building. Fortunately, advances in construction technologies have put us on the verge of a revolution.

> **Many of the techniques we use during construction today were invented in ancient Egypt or Rome.**



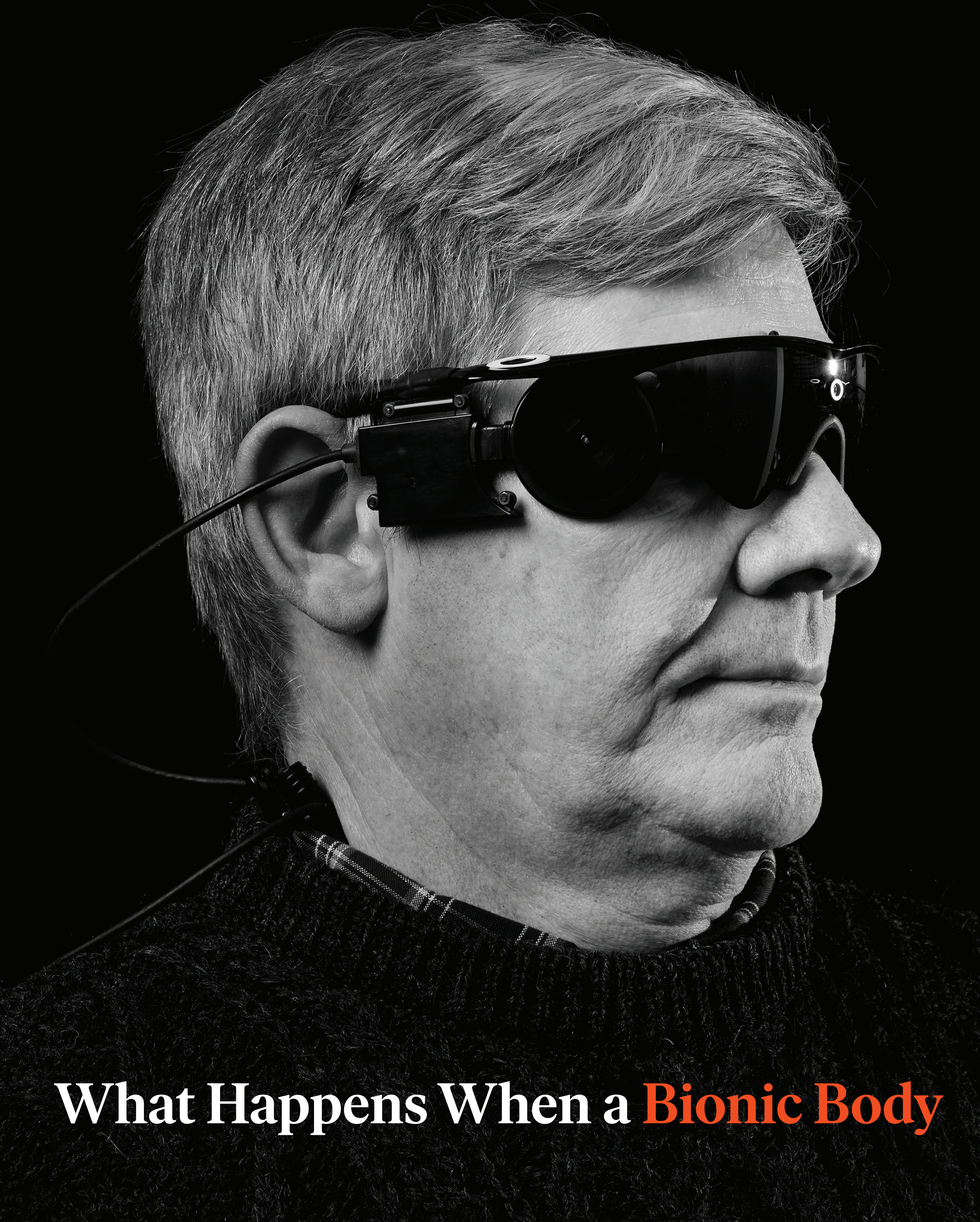
Many of the construction techniques we use today were invented in ancient Egypt or Rome. Examples include concrete, the weighted plumb line to determine true vertical with a square to derive the horizontal from that, and snapping a chalk-covered string on the ground to lay out a straight line for a wall. The arch, developed by the Romans, has been superseded by steel beams for the transom over windows and doors, and now digitalization is encroaching on these other time-tested techniques.

Simultaneous localization and mapping (SLAM) was developed in the 1980s and used originally to enable indoor robots to map their surroundings and locate themselves within them, using cameras, lidar, and other sensors. It is now used on construction sites to reconstruct a full three-dimensional model of an environment, just by walking around with one of the latest smartphones, which incorporate depth sensors. These techniques allow the dimensions of partially constructed buildings to be uploaded to CAD models. Augmented reality then shows workers exactly where to place the next components. Larger and larger components of new buildings are being built off-site in factories, making construction more efficient and less labor intensive.

For thousands of years our buildings have been rectangular and largely built in place by craftsmen. In the second half of the 20th century we began mass-producing small-scale building components. These allowed enormous lightweight curtain walls of identical elements, whether of glass, aluminum, or thin stone, mounted to the structural elements, giving buildings a much lighter and different look. But the identical mounting components meant that rectangular designs were pretty much all that could be produced. Now, with 3D printing along with general-form geometric CAD, new shapes will become possible even for low-cost buildings. And as 3D printing progresses to larger and stronger components, even the structural elements will be freed from the tyranny of perpendicularity.

Combine all these factors and a dazzling possibility emerges. Imagine using cheap wind- and solar-generated electricity to pull carbon out of the atmosphere and turn it into feedstock for large-scale 3D printing of building components. Whoever commercializes that will have a shot at pulling off a remarkable first: building the first megabusiness—and megafortune—that reduces atmospheric carbon rather than increasing it. ■

Illustration by Edmon de Haro



What Happens When a Bionic Body

Part Becomes Obsolete?

Blind people with Second Sight's retinal implants found out

By ELIZA STRICKLAND & MARK HARRIS

Ross Doerr [left] and Barbara Campbell [right] were both delighted with the retinal implants that gave them artificial vision. Then the company behind the implants, Second Sight, stopped making them.

Photos, left: Bob O'Connor; right: Nathaniel Welch/Redux

Barbara Campbell's retinal implant abruptly powered down during a subway transfer in Manhattan, and never worked again.

BARBARA CAMPBELL was walking through a New York City subway station during rush hour when her world abruptly went dark. For four years, Campbell had been using a high-tech implant in her left eye that gave her a crude kind of bionic vision, partially compensating for the genetic disease that had rendered her completely blind in her 30s. "I remember exactly where I was: I was switching from the 6 train to the F train," Campbell tells *IEEE Spectrum*. "I was about to go down the stairs, and all of a sudden I heard a little 'beep, beep, beep' sound."

It wasn't her phone battery running out. It was her Argus II retinal implant system powering down. The patches of light and dark that she'd been able to see with the implant's help vanished.

Terry Byland is the only person to have received this kind of implant in both eyes. He got the first-generation Argus I implant, made by the company Second Sight Medical Products, in his right eye in 2004 and the subsequent Argus II implant in his left 11 years later. He helped the company test the technology, spoke to the press movingly about his experiences, and even met Stevie Wonder at a conference. "[I] went from being just a person that was doing the testing to being a spokesman," he remembers.

Yet in 2020, Byland had to find out secondhand that the company had abandoned the technology and was on the verge of going bankrupt. While his two-implant system is still working, he doesn't know how long that will be the case. "As long as nothing goes wrong, I'm fine," he says. "But if something does go wrong with it, well, I'm screwed. Because there's no way of getting it fixed."

Ross Doerr, another Second Sight patient, doesn't mince words: "It is fantastic technology and a lousy company," he says. He received an implant in one eye in 2019 and remembers seeing the shining lights of Christmas trees that holiday season. He was thrilled to learn in early 2020 that he was eligible for software upgrades that could further improve his vision. Yet in the early months of the COVID-19 pandemic, he heard troubling rumors about the company and called his Second Sight vision-rehab therapist. "She said, 'Well, funny you should call. We all just got laid off,' " he remembers. "She said, 'By the way, you're not getting your upgrades.' "

These three patients, and more than 350 other blind people around the world with Second Sight's implants in their eyes, find themselves in a world in which the technology that transformed their lives is just another obsolete gadget. One technical hiccup, one broken wire, and they lose their artificial vision, possibly forever. To add injury to insult: A defunct Argus system in the eye could cause medical complications or interfere with procedures such as MRI scans, and it could be painful or expensive to remove.

Neural implants—devices that interact with the nervous system, either on its periphery or in the brain—are part of a rapidly growing category of medicine called electroceuticals. Some technologies are well established, like deep-brain stimulators that reduce tremors in people with Parkinson's disease. But recent advances in neuroscience have sparked a gold rush in brain tech, with the outsize investments epitomized by Elon Musk's buzzy brain-implant company, Neuralink. Companies talk of reversing depression, treating Alzheimer's disease, restoring mobility, or even dangle the promise of superhuman cognition.

Not all these companies will succeed, and Los Angeles–based Second Sight provides a cautionary tale for bold entrepreneurs interested in brain tech. What happens when cutting-edge implants fail, or simply fade away like yesterday's flip phones and Betamax? Even worse, what if the companies behind them go bust?

After Second Sight discontinued its retinal implant in 2019 and nearly went out of business in 2020, a public offering in June 2021 raised US $57.5 million at $5 per share. The company promised to focus on its ongoing clinical trial of a brain implant, called Orion, that also provides artificial vision. But its stock price plunged to around $1.50, and in February 2022, just before this article was published, the company announced a proposed merger with an early-stage biopharmaceutical company called Nano Precision Medical (NPM). None of

BEATRICE DE GEA/THE NEW YORK TIMES/REDUX

Second Sight's executives will be on the leadership team of the new company, which will focus on developing NPM's novel implant for drug delivery.

Second Sight's leadership declined to be interviewed for this article but did provide a statement prior to the merger announcement. It said, in part: "We are a recognized global leader in neuromodulation devices for blindness and are committed to developing new technologies to treat the broadest population of sight-impaired individuals."

Spectrum pieced together Second Sight's story by interviewing half a dozen patients, a company cofounder, and eight doctors or researchers involved with the company. In their telling, the company took hundreds of patients on a roller-coaster ride of technological innovations, regulatory successes, medical and financial setbacks, and a near-total meltdown. Now, as the company fades away, the future of high-tech vision implants seems blurrier than ever.

SECOND SIGHT BEGAN with a flash of light. In 1991, Robert Greenberg, an electrical engineer turned medical student, stood in an operating room watching as a retinal surgeon inserted a tiny wire into the eye of a blind patient, who was awake and under local anesthesia. When the wire touched the patient's retina and delivered a minuscule jolt of electric current, the man reported a spot of light in his pitch-black field of vision. The surgeon inserted a second wire, and the man saw two spots of light. "If you can create two spots, it seemed obvious to me that you could do a lot of spots and create images," Greenberg said in a 2011 interview for a *Spectrum* article. "We just needed to build a device."

Ross Doerr couldn't get an MRI to check for a brain tumor because his doctors couldn't get information about his implant from Second Sight.

Of course, it wasn't that easy. Greenberg spent many years developing the technology while working at the Alfred Mann Foundation, a nonprofit organization that develops biomedical devices; he spun off the company Second Sight with three cofounders in 1998. The clinical trials of the first-generation Argus I (with a 16-electrode array) and the subsequent Argus II retinal implant (with a 60-pixel array) resulted in European regulatory approval in 2011 and U.S. approval in 2013.

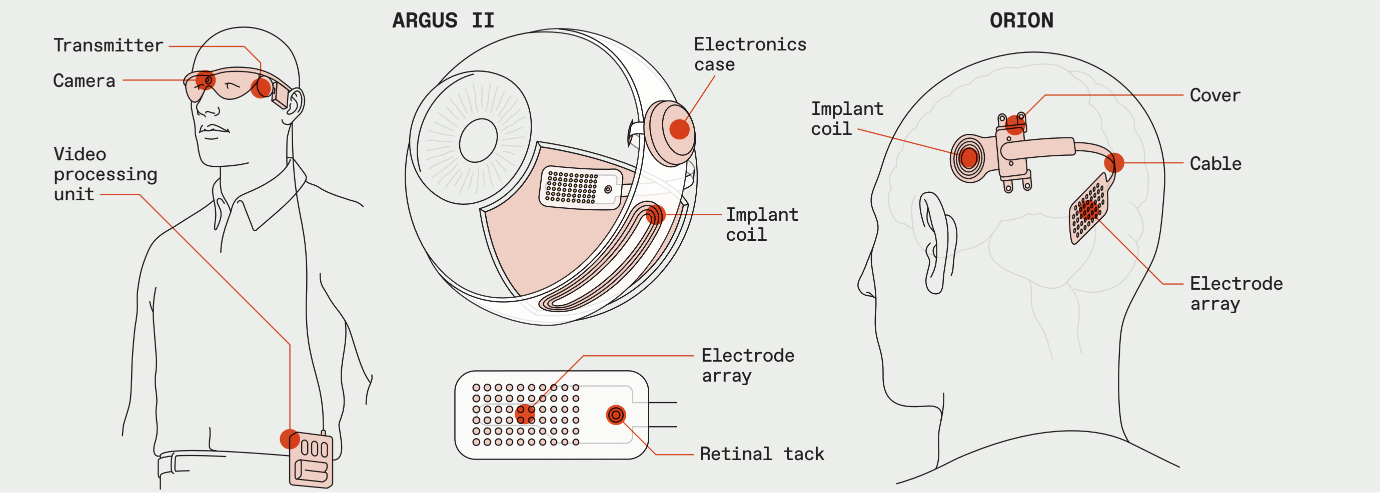
The Argus II system consists of more than just the implant, which is surgically implanted in a procedure that takes about 4 hours. The user also wears special glasses outfitted with a small camera that sends video down a wire to a video processing unit (VPU), typically attached to the user's belt. The VPU reduces the images to patterns of 60 black-and-white pixels and sends them back to a transponder in the glasses, which beams them wirelessly to an antenna on the outside of the eye. From there, the signal goes to the 60-electrode array attached to the patient's retina. The electrodes stimulate the eye in different patterns multiple times per second, creating flashes of light that correspond to the low-resolution video feed. Essentially, the electrodes take the place of the photoreceptor cells in a healthy eye that respond to light and send information up the optic nerve to the brain.

Normal vision, this is not. Patients and doctors alike stress that the Argus II provides a kind of artificial vision, really a brand-new sense that people must learn how to use. Argus II users perceive shades of gray that appear and disappear as they move their heads. "This was the first of its kind, it was a fledgling technology," Greenberg told *Spectrum* in a recent interview. "We asked ourselves a lot: What's good enough? There's no doubt that it was very crude." In its statement, Second Sight told *Spectrum* that most patients saw well enough to assist with basic locomotion.

But the company admits that the results varied. While some patients could make out the white stripes of a crosswalk against a dark road or the brightness of a face turned toward them, others struggled to see even basic

Photo by Bob O'Connor

SECOND SIGHT'S TWO TECHNOLOGIES for artificial vision both start with a camera that streams video to a video processing unit. The VPU converts the images to simple patterns of 60 pixels and sends that information to a transmitter on the user's glasses. For Argus II, the patterns go to an implant in the retina. For Orion, which is now in clinical trials, the information goes to an implant in the brain.



patterns and shapes. Still, for many, it was worth it. Doerr remembers his attitude before the surgery: "Although it isn't normal vision, it's 100 percent better than what I have now."

Jeroen Perk, who lives in the Netherlands, lost his sight almost completely by the age of 19. In 2013, at the age of 36, Perk became one of the youngest people to receive an Argus II. He was a success story: Within just a couple of years, Perk was shown in Second Sight videos skiing and shooting arrows.

Lucian Del Priore was one of the physicians involved in the clinical trials; he did the implantation for Barbara Campbell while at NewYork-Presbyterian, in New York City. He remembers the excitement when the U.S. Food and Drug Administration approved the Argus II technology for people with a genetic condition called retinitis pigmentosa, and notes that there were no other options for such patients.

"These people were completely in the dark," he says. "They couldn't tell the difference between a bright day at the beach and being in a coal mine in Pittsburgh. The idea that they were getting some kind of vision, it was kind of electrifying—for the patients and the doctors."

WHILE THE ARGUS II was technically impressive, it faced financial headwinds. Second Sight was selling the Argus II for around $150,000 in the United States—about five times as much as other neuromodulation devices, according to Greenberg. But even so, he says, the company was losing money: "With all the overhead of sales and regulatory people, it wasn't profitable."

Moreover, implanting the Argus II was just the start of a long, tough journey for patients. Second Sight employed its own vision-rehabilitation specialists to work one-on-one with implantees, often for months or years. One Argus II patient estimated that the total cost of the device, surgery, and rehabilitation was $497,000.

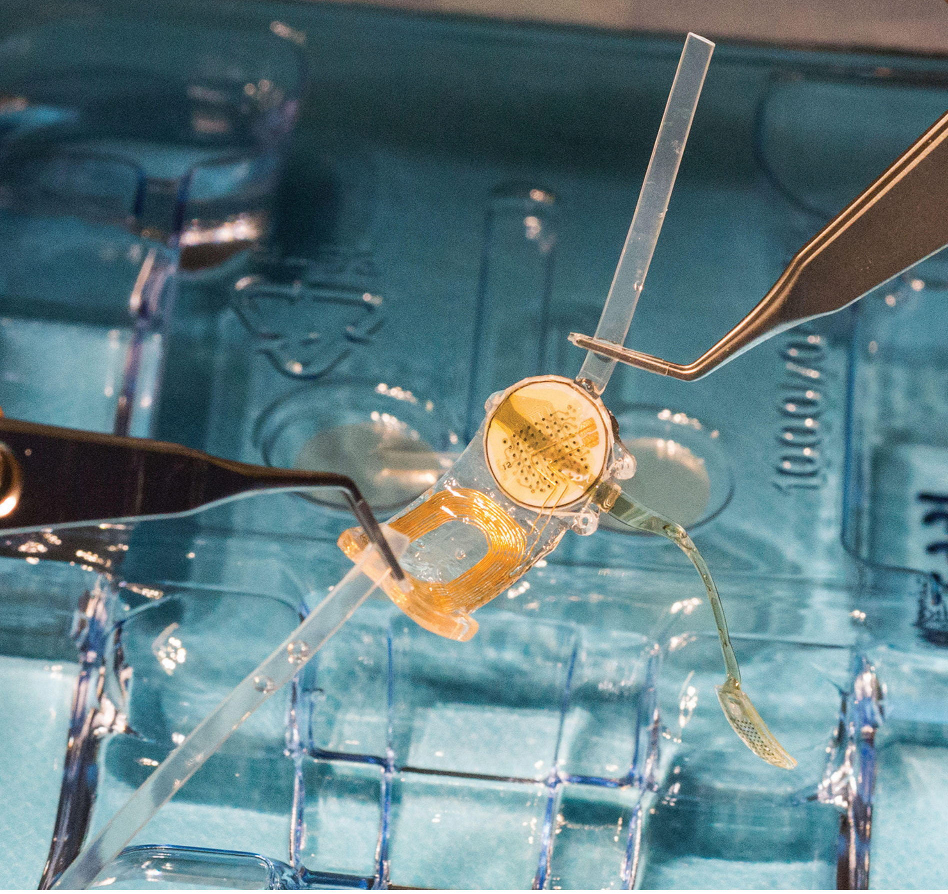
A positive outcome was far from certain. Although Linda Kirk was the subject of an optimistic news story on receiving her Argus II in New York in 2017, she found the implant more distracting than enabling. "I really wanted to be able to tell them, this is great; it's a success. And I couldn't do that," she tells *Spectrum*. Kirk stopped using the device a couple of years later.

At the nonprofit Lighthouse International, a senior fellow in vision science named Aries Arditi was a principal investigator for the Argus II clinical trial. Arditi says his experiences with patients slowly soured him on the technology. He tells *Spectrum* that in his decades of work with people who were born sighted and later lost their vision, he's learned that "they often develop a desperate hope for something that will help and are willing to try anything." Arditi feels that Second Sight promised more than it delivered. "I found it very disturbing that [Second Sight] sold so many of these devices to patients who were relying on hope rather than proven performance."

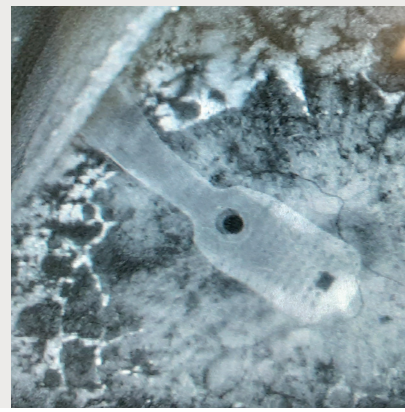
Arditi also says that he did a research study including nearly all the U.S. participants in the Argus II clinical trial that showed "weakness" with the device's vision quality. He says Second Sight wouldn't let him publish or present the results; the company says it disagreed with his analysis and discouraged him from publishing.

Barbara Campbell, who received her implant during the clinical trial of the Argus II, did find the bionic vision system useful. As a New York City resident, she used it on the busy sidewalks and while taking a subway or bus. "The more I used it, the benefits increased," she remem-

Illustration by James Provost



The Argus II retinal implant takes the place of photoreceptors in the eye that have stopped working. Its electrode array [below] stimulates cells that send information to the optic nerve. The attached implant coil and electronics case [left] receive the stimulation patterns from the user's glasses.



LEFT: PHANIE/ALAMY; RIGHT: ROSS DOERR

bers. "I think I was retraining my brain to see stuff." But in 2013, after four years of regular use, Campbell's system shut down in the subway station, and despite some repair attempts by Second Sight, never worked again. While she talked with her doctors about having the implant removed, she ultimately decided that the risks of another surgery weren't worth it. She still has the defunct technology in her left eye.

SIMPLY NOT WORKING isn't the worst thing that could happen—there's also the possibility of medical problems. Second Sight conducted an FDA-mandated postapproval study of the Argus II, following 30 patients from 2007 to 2019. Over that time, 36 serious and 152 nonserious "adverse events" were observed. The FDA did not make the study's final report available to *Spectrum*, and a Freedom of Information Act request filed in May 2021 has yet to be fulfilled.

However, the FDA also maintains a public database called Manufacturer and User Facility Device Experience, or MAUDE, where manufacturers are required (and health care professionals and patients are encouraged) to submit reports of serious adverse events.

Spectrum analyzed all 90 MAUDE reports for the Argus II, submitted from 2014 to 2020. These reports are unverified and could be duplicate, biased, inaccurate, or incomplete, warns the FDA. While some described inflammation, infection, or pain that could be managed with medication, nearly 80 percent reported a surgical intervention. The reasons for surgery included hemorrhages, low eye pressure and, in about 15 percent of cases, detached retinas.

To be sure, such outcomes were not very common. Data from 2017 (published in 2020) showed that 83 percent of 244 postapproval patients had experienced no serious events after two years.

Terry Byland did not encounter any problems with his 2004 Argus I implant. In fact, when Second Sight offered him the Argus II, he was eager to try it. "Once you get a taste of being able to see certain things again, you want to continue on and make it better," he tells *Spectrum*. By June 2015, Byland was the only person on the planet with two bionic eyes.

The jump from the Argus I's 16 electrodes to 60 in the newer technology improved Byland's vision, and it seemed like more advances were just around the corner. During a series of tests at the University of Southern California and Second Sight in 2016 and 2017, Byland was told about "virtual electrodes," that is, software upgrades that would boost his system fourfold to around 250 pixels, as well as a new video processing unit. "I was sold," he says. "I felt like we were on the verge of really making a big breakthrough."

Other Argus II patients *Spectrum* spoke with were also told they would be getting upgrades, such as a digital camera, thermal imaging, and even facial recognition software. In 2016, a USC professor even raised the possibility of color vision.

By 2018, Byland's impressions had shifted. Second Sight continued to ask him to do promotional visits, but testing had slacked off—and there was no sign of any new technology. "It just felt like maybe somebody there wasn't being completely honest with me," he says.

COMPANY COFOUNDER Greenberg says Second Sight's long-term plan was always to pivot to a brain implant that would bypass the eye altogether and directly stimulate the visual cortex. A neural device could help more people with vision problems, even those who weren't eligible for an Argus II implant because of severe damage to the retina or optic nerve. But Greenberg wasn't able to steer the company through that transition.

Greenberg's relationship with Second Sight's investors had been worsening over the years; he stepped down as CEO in 2015 and then left the board of directors in 2018, a move that he has characterized as a forced departure but that he declined to discuss with *Spectrum* because of a non disclosure agreement (NDA).

On 18 July 2019, Second Sight sent Argus patients a letter saying it would be phasing out the retinal implant technology to clear the way for the development of its next-generation brain implant for blindness, Orion, which had begun a clinical trial with six patients the previous year. The U.S. National Institutes of Health is funding that trial as a $6.4 million project over five years.

"The leadership at the time didn't believe they could make [the Argus] part of the business profitable," Greenberg says. "I understood the decision, because I think the size of the market turned out to be smaller than we had thought."

Second Sight was quick to assure Argus patients that its support of their retinal devices would not change. "Second Sight will be maintaining a full team of Customer Care and Vision Rehab Specialists accessible to you as we have in the past," read the letter. "In addition, we have taken all measures to ensure the ongoing supply needs for your device."

However, the letter's promises were already looking shaky, according to one ex-engineer at the company, who asked not to be named because they had also signed an NDA. "We didn't really support the basic Argus after that," the engineer tells *Spectrum*. "We didn't sell any more, we didn't make any more, we didn't have anything to do with it anymore."

And worse was yet to come, for Argus and Orion patients alike. In February 2020, the senior director of implant R&D left the company, swiftly followed by its CEO. On 30 March, Second Sight laid off the majority of its remaining employees and announced its "intention to wind down operations," citing the impact of the COVID-19 pandemic on its ability to secure financing. Within weeks, most of its physical assets—including manufacturing equipment, scientific instruments, laptops, and shelving—went up for sale at auction.

Second Sight didn't inform any of its patients of the company's collapse. "No letter, email, or telephone call," Ross Doerr wrote on Facebook after weeks of fruitlessly trying to contact the company. "Those of us with this implant are figuratively and literally in the dark."

The implications of Second Sight's implosion would soon strike home for Doerr. While using the Argus II for more than a few hours had always caused him to feel a little dizzy, early in 2020 he started to experience severe vertigo.

Doerr's doctor scheduled an MRI scan to rule out a brain-stem tumor. But because an MRI's intense magnetic fields can interact with the Argus II, MRI providers are instructed to contact Second Sight before performing any scans—and Second Sight wasn't picking up the phone. Doerr eventually got a CT scan instead, which found nothing. "I still don't know if I have a brain-stem tumor or not," he tells *Spectrum*.

Jeroen Perk also suffered from the transition. A regular user of the Argus II for up to 9 hours a day, Perk was using the system in November 2020 when the video processing unit (VPU) fell from his belt to the ground and shattered. "I had no vision, no Argus, and no support from Second Sight," he remembers.

For a week Perk considered his options, including having the device removed from his retina. "My conclusion was, I must have [my vision] back," he says. Perk shared his situation with the Argus II community in Europe, asking if anyone had spare parts. He quickly heard back from a patient who was no longer using the device and from a doctor with a spare VPU. By February 2021, he had a refurbished system, and Perk is now happily using it. "It is a pity that the Argus is not going any further," he says. "But I'm a lucky bastard. I never have any regrets about doing this."

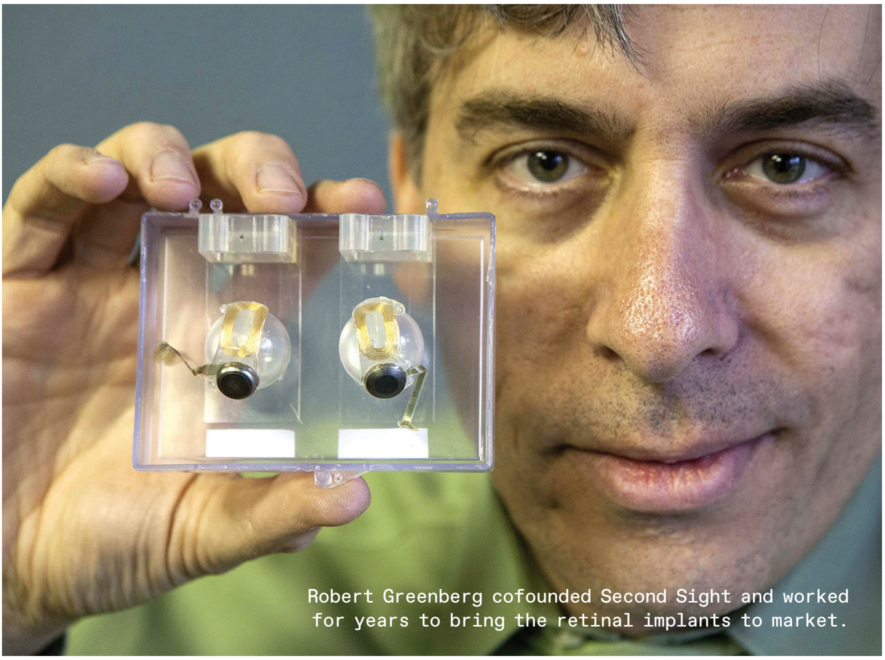
In its statement to *Spectrum*, Second Sight says that during its financial difficulties, its reduced workforce "was unable to continue the previous level of support and communication for Argus II centers and users." After *Spectrum* contacted Second Sight, the company sent letters to Argus clinicians and users stating that "we will do our best to provide virtual support" to physicians and that it has a limited supply of VPUs and glasses for replacements. No repairs or replacements are possible, however, for the implants themselves.

It's unclear what Second Sight's proposed merger means for Argus patients. The day after the merger was announced, Adam Mendelsohn, CEO of Nano Precision Medical, told *Spectrum* that he doesn't yet know what contractual obligations the combined company will have to Argus and Orion patients. But, he said, NPM will try to do what's "right from an ethical perspective." The past, he added in an email, is "simply not relevant to the new future."

EVEN CLINICIANS WERE taken by surprise by Second Sight's collapse in 2020. Neurosurgeon Nader Pouratian, now at UT Southwestern Medical Center, is one of the researchers involved in the clinical trial of the Orion brain implant. "Up until days before Second Sight announced that it was reorganizing, we were actively planning the next stages of the research," he tells *Spectrum*. Pouratian says the Orion patients were worried about having unsupported devices left in their brains: "There was a lot of anxiety among some patients that they were going to be left high and dry."

Benjamin Spencer is one of the six Orion patients. He had been blind for 26 years when he received his neural implant in 2018, and he was initially delighted with it. When he first used it at home with his family, "it was amazing," he says. "Here's my wife—I've never seen [her] other than in my dreams." He tells *Spectrum* that the Orion enabled him to walk through a grocery store and do his shopping without using a cane.

Spencer's feelings about the device shifted when he heard that Second Sight was in trouble. He says the lack of clarity about the company's future "leaves you in a very, very vulnerable spot." He says that all the Orion patients "were very much contemplating, 'Are we going to get this removed now, before there's no funding, before there's no assurance?' " One of the six did choose to have the device removed in order to safely have an MRI scan. As for Spencer, he now uses the



Robert Greenberg cofounded Second Sight and worked for years to bring the retinal implants to market.

RINGO CHIU/ZUMA PRESS/ALAMY

Orion sparingly, and plans to have the implant removed at the end of the study. "Had I known three years ago what I know now, I probably wouldn't have signed up for it," he says.

Greenberg, the former Second Sight CEO, is now the CEO and chairman of the Alfred Mann Foundation, which is involved in the Orion clinical trial. After the announcement of the proposed merger, he told *Spectrum*: "I still believe Orion has the potential to help many blind patients in a fiscally responsible way."

The neurosurgeons involved in the work have been enthusiastic about the Orion technology. Daniel Yoshor, who implanted two Orion devices while chair of neurosurgery at Baylor College of Medicine, tells *Spectrum* that the technology was "an important first step." Recently, he has experimented with stimulation patterns that give Orion patients more visual acuity, even enabling them to recognize large letters on a computer screen.

Neurosurgeon Pouratian says that the 60-electrode brain implant is the most high-tech and precise neural implant to date, for any application. "From a technological standpoint, it's pretty amazing in terms of its capabilities," he says.

A much larger clinical trial would be required to gain FDA approval of the Orion. However, in the days after the merger announcement, Nano Precision Medical CEO Mendelsohn told *Spectrum* that the merged company is "not committing to any sort of timeline with the Orion," and emphasized that its priority will be NPM's drug-delivery device. The new company will also "develop some strategic options for what makes sense going forward with the Orion technology," Mendelsohn says.

SECOND SIGHT MAY have given up on its retinal implant, but other companies still see a need—and a market—for bionic vision without brain surgery. Paris-based Pixium Vision is conducting feasibility trials to see if its Prima system can help patients with age-related macular degeneration, a much more common condition than retinitis pigmentosa.

Daniel Palanker, a professor of ophthalmology at Stanford University who licensed his technology to Pixium, says the Prima implant is smaller, simpler, and cheaper than the Argus II. But he argues that it is Prima's superior image resolution that will make Pixium Vision a success. "If you provide excellent vision, there will be lots of patients," he tells *Spectrum*. "If you provide crappy vision, there will be very few."

Some clinicians involved in the Argus II work are trying to salvage what they can from the technology. Gislin Dagnelie, an associate professor of ophthalmology at Johns Hopkins University School of Medicine, has set up a network of clinicians who are still working with Argus II patients. The researchers are experimenting with a thermal camera to help users see faces, a stereo camera to filter out the background, and AI-powered object recognition. These upgrades are unlikely to result in commercial hardware today but could help future vision prostheses.

Failure is an inevitable part of innovation. The Argus II was an innovative technology, and progress made by Second Sight may pave the way for other companies that are developing bionic vision systems. But for people considering such an implant in the future, the cautionary tale of Argus patients left in the lurch may make a tough decision even tougher. Should they take a chance on a novel technology? If they do get an implant and find that it helps them navigate the world, should they allow themselves to depend upon it?

Abandoning the Argus II technology—and the people who use it—might have made short-term financial sense for Second Sight, but it's a decision that could come back to bite the merged company if it does decide to commercialize a brain implant, believes Doerr.

"Who's going to swallow their marketing for the Orion?" he says. Doerr is glad he has Second Sight's technology in his retina instead of his brain tissue. "If it has to come out, it's going to be bothersome," he says, "[but] nobody is messing with my brain."

NPM's Mendelsohn says the merged company will explore its options with Orion and tells *Spectrum* that "there's a genuinely strong desire to try to find the best strategic option to bring [the Orion] technology to patients." If development of the neural implant does go ahead, at least the new company will have the benefit of 20/20 hindsight. "We spend a lot of time thinking about the learnings from the Argus," says Mendelsohn, "and how not to repeat going forward." ■

NASA's New Shortcut to Fusion Power

LATTICE CONFINEMENT FUSION ELIMINATES MASSIVE MAGNETS AND POWERFUL LASERS

By
Bayarbadrakh Baramsai, Theresa Benyo, Lawrence Forsley & Bruce Steinetz

PHYSICISTS FIRST SUSPECTED MORE THAN A CENTURY AGO that the fusing of hydrogen into helium powers the sun. It took researchers many years to unravel the secrets by which lighter elements are smashed together into heavier ones inside stars, releasing energy in the process. And scientists and engineers have continued to study the sun's fusion process in hopes of one day using nuclear fusion to generate heat or electricity. But the prospect of meeting our energy needs this way remains elusive. ● The extraction of energy from nuclear fission, by contrast, happened relatively quickly. Fission in uranium was discovered in 1938, in Germany, and it was only four years later that the first nuclear "pile" was constructed in Chicago, in 1942.

Photo-illustration by Edmon de Haro

There are currently about 440 fission reactors operating worldwide, which together can generate about 400 gigawatts of power with zero carbon emissions. Yet these fission plants, for all their value, have considerable downsides. The enriched uranium fuel they use must be kept secure. Devastating accidents, like the ones at Chernobyl in Ukraine and Fukushima in Japan, can leave areas uninhabitable. Fission waste by-products need to be disposed of safely, and they remain radioactive for thousands of years. Consequently, governments, universities, and companies have long looked to fusion to remedy these ills.

Among those interested parties is NASA. The space agency has significant energy needs for deep-space travel, including probes and crewed missions to the moon and Mars. For more than 60 years, photovoltaic cells, fuel cells, or radioisotope thermoelectric generators (RTGs) have provided power to spacecraft. RTGs, which rely on the heat produced when nonfissile plutonium-238 decays, have demonstrated excellent longevity—both Voyager probes use such generators and remain operational nearly 45 years after their launches, for example. But these generators convert heat to electricity at roughly 7.5 percent efficiency. And modern spacecraft need more power than an RTG of reasonable size can provide.

One promising alternative is lattice confinement fusion (LCF), a type of fusion in which the nuclear fuel is bound in a metal lattice. The confinement encourages positively charged nuclei to fuse because the high electron density of the conductive metal reduces the likelihood that two nuclei will repel each other as they get closer together.

We and other scientists and engineers at NASA Glenn Research Center, in Cleveland, are investigating whether this approach could one day provide enough power to operate small robotic probes on the surface of Mars, for example. LCF would eliminate the need for fissile materials such as enriched uranium, which can be costly to obtain and difficult to handle safely. LCF promises to be less expensive, smaller, and safer than other strategies for harnessing nuclear fusion. And as the technology matures, it could also find uses here on Earth, such as for small power plants for individual buildings, which would reduce fossil-fuel dependency and increase grid resiliency.

PHYSICISTS HAVE LONG thought that fusion should be able to provide clean nuclear power. After all, the sun generates power this way. But the sun has a tremendous size advantage. At nearly 1.4 million kilometers in diameter, with a plasma core 150 times as dense as liquid water and heated to 15 million °C, the sun uses heat and gravity to force particles together and keep its fusion furnace stoked.

On Earth, we lack the ability to produce energy this way. A fusion reactor needs to reach a critical level of fuel-particle density, confinement time, and plasma temperature (called the Lawson Criteria after creator John Lawson) to achieve a net-positive energy output. And so far, nobody has done that.

Fusion reactors commonly utilize two different hydrogen isotopes: deuterium (one proton and one neutron) and tritium (one proton and two neutrons). These are fused into helium nuclei (two protons and two neutrons)—also called alpha particles—with an unbound neutron left over.

Existing fusion reactors rely on the resulting alpha particles—and the energy released in the process of their creation—to further heat the plasma. The plasma will then drive more nuclear reactions with the end goal of providing a net power gain. But there are limits. Even in the hottest plasmas that reac-

The deuterated erbium (chemical symbol ErD_3) is placed into thumb-size vials, as shown in this set of samples from a 20 June 2018 experiment. At left, the vials are arrayed pre-experiment, with wipes on top of the metal to keep the metal in position during the experiment. The metal has begun to crack and break apart, indicating it is fully saturated with deuterium. Below, the vials are placed upside down to align the metal with the gamma ray beam. Gamma rays have turned the clear glass amber.

NASA

tors can create, alpha particles will mostly skip past additional deuterium nuclei without transferring much energy. For a fusion reactor to be successful, it needs to create as many direct hits between alpha particles and deuterium nuclei as possible.

In the 1950s, scientists created various magnetic-confinement fusion devices, the most well known of which were Andrei Sakharov's tokamak and Lyman Spitzer's stellarator. Setting aside differences in design particulars, each attempts the near-impossible: Heat a gas enough for it to become a plasma and magnetically squeeze it enough to ignite fusion—without letting the plasma escape.

Inertial-confinement fusion devices followed in the 1970s. They used lasers and ion beams either to compress the surface of a target in a direct-drive implosion or to energize an interior target container in an indirect-drive implosion. Unlike magnetically confined reactions, which can last for seconds or even minutes (and perhaps one day, indefinitely), inertial-confinement fusion reactions last less than a microsecond before the target disassembles, thus ending the reaction.

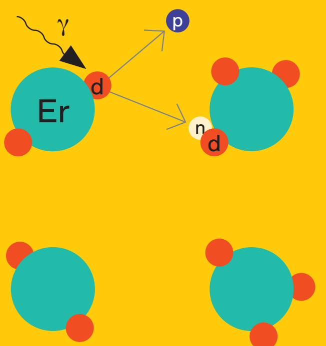
Both types of devices can create fusion, but so far they are incapable of generating enough energy to offset what's needed to initiate and maintain the nuclear reactions. In other words, more energy goes in than comes out. Hybrid approaches, collectively called magneto-inertial fusion, face the same issues.

Current fusion reactors also require copious amounts of tritium as one part of their fuel mixture. The most reliable source of tritium is a *fission* reactor, which somewhat defeats the purpose of using fusion.

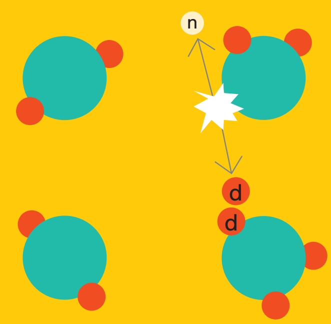
The fundamental problem of these techniques is that the atomic nuclei in the reactor need to be energetic enough—meaning hot enough—to overcome the Coulomb barrier, the natural tendency for the positively charged nuclei to repel one another. Because of the Coulomb barrier, fusing atomic nuclei have a very small fusion cross section, meaning the probability that two particles will fuse is low. You can increase the cross section by raising the plasma temperature to 100 million °C, but that requires increasingly heroic efforts to confine the plasma. As it stands, after billions of dollars of investment and decades of research, these approaches, which we'll call "hot fusion," still have a long way to go.

THE BARRIERS TO hot fusion here on Earth are indeed tremendous. As you can imagine, they'd be even more overwhelming on a spacecraft, which can't carry a tokamak or stellarator onboard. Fission reactors are being considered as an alternative—NASA successfully tested the Kilopower fission reactor at the Nevada National Security Site in 2018 using a uranium-235 core about the size of a paper towel roll.

Lighting the Fusion Fire

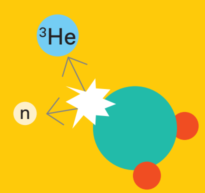


In lattice confinement fusion (LCF), a beam of gamma rays is directed at a sample of erbium [shown here] or titanium saturated with deuterons. Occasionally, gamma rays with sufficient energy will break apart a deuteron into its constituent proton and neutron.

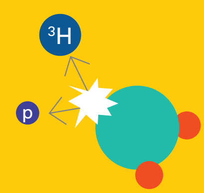


The neutron collides with another deuteron in the lattice, imparting some of its own momentum to the deuteron. The electron-screened deuteron is now energetic enough to overcome the Coulomb barrier, which would typically repel it from another deuteron.

Deuteron-Deuteron Fusion

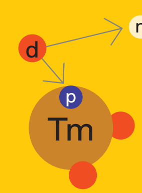


When the energetic deuteron fuses with another deuteron in the lattice, it can produce a helium-3 nucleus (helion) and give off useful energy. A leftover neutron could provide the push for another energetic deuteron elsewhere.

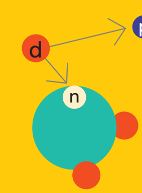


Alternatively, the fusing of the two deuterons could result in a hydrogen-3 nucleus (triton) and a leftover proton. This reaction also produces useful energy.

Stripping and OP Reaction



Another possible reaction in LCF would happen if an erbium atom rips apart the energetic deuteron and absorbs the proton. The extra proton changes the erbium atom to thulium and releases energy.



If the erbium atom absorbs the neutron, it becomes a new isotope of erbium. This is an Oppenheimer-Phillips (OP) stripping reaction. The proton from the broken-apart deuteron heats the lattice.

Rich Martin [left], a research engineer, and coauthor Bruce Steinetz, principal investigator for the LCF project's precursor experiment, examine samples after a run.

The Kilopower reactor could produce up to 10 kilowatts of electric power. The downside is that it requires highly enriched uranium, which brings additional launch safety and security concerns. This fuel also costs a lot.

But fusion could still work, even if the conventional fusion approaches are nonstarters. LCF could be compact enough, light enough, and simple enough to serve for spacecraft.

How does LCF work? Remember that we earlier mentioned deuterium, the isotope of hydrogen with one proton and one neutron in its nucleus. Deuterided metals—erbium and titanium, in our experiments—have been "saturated" with either deuterium or deuterium atoms stripped of their electrons (deuterons). This is possible because the metal naturally exists in a regularly spaced lattice structure, which creates equally regular slots in between the metal atoms for deuterons to nest.

In a tokamak or a stellarator, the hot plasma is limited to a density of 10^{14} deuterons per cubic centimeter. Inertial-confinement fusion devices can momentarily reach densities of 10^{26} deuterons per cubic centimeter. It turns out that metals like erbium can indefinitely hold deuterons at a density of nearly 10^{23} per cubic centimeter—far higher than the density that can be attained in a magnetic-confinement device, and only three orders of magnitude below that attained in an inertial-confinement device. Crucially, these metals can hold that many ions *at room temperature.*

The deuteron-saturated metal forms a plasma with neutral charge. The metal lattice confines and electron-screens the deuterons, keeping each of them from "seeing" adjacent deuterons (which are all positively charged). This screening increases the chances of more direct hits, which further promotes the fusion reaction. Without the electron screening, two deuterons would be much more likely to repel each other.

Using a metal lattice that has screened a dense, cold plasma of deuterons, we can jump-start the fusion process using what is called a Dynamitron electron-beam accelerator. The electron beam hits a tantalum target and produces gamma rays, which then irradiate thumb-size vials containing titanium deuteride or erbium deuteride.

When a gamma ray of sufficient energy—about 2.2 megaelectron volts (MeV)—strikes a deuteron in the metal lattice, the deuteron breaks apart into its constituent proton and neutron. The neutron may collide with another deuteron, accelerating it much as a pool cue accelerates a ball when striking it. This second, energetic deuteron then goes through one of two processes: screened fusion or a stripping reaction.

In screened fusion, which we have observed in our experiments, the energetic deuteron fuses with another deuteron in the lattice. The fusion reaction will result in either a helium-3 nucleus and a leftover neutron or a hydrogen-3 nucleus and a leftover proton. These fusion products may fuse with other deuterons, creating an alpha particle, or with another helium-3 or hydrogen-3 nucleus. Each of these nuclear reactions releases energy, helping to drive more instances of fusion.

In a stripping reaction, an atom like the titanium or erbium in our experiments strips the proton or neutron from the deuteron and captures that proton or neutron. Erbium, titanium, and other heavier atoms preferentially absorb the neutron because the proton is repulsed by the positively charged nucleus (called an Oppenheimer-Phillips reaction). It is theoretically possible, although we haven't observed it, that the electron screening might allow the proton to be captured, trans-

NASA

Who's Who in the Fusion Zoo

p

PROTON: Positively charged protons (along with neutrons) make up atomic nuclei. One component of lattice confinement fusion (LCF) may occur when a proton is absorbed by an erbium atom in a deuteron stripping reaction.

n

NEUTRON: Neutrally charged neutrons (along with protons) make up atomic nuclei. In fusion reactions, they impart energy to other particles such as deuterons. They also can be absorbed in Oppenheimer-Phillips reactions.

Er Ti

ERBIUM & TITANIUM: Erbium and titanium are the metals of choice for LCF. Relatively colossal compared with the other particles involved, they hold the deuterons and screen them from one another.

d

DEUTERIUM: Deuterium is hydrogen with one proton and one neutron in its nucleus (hydrogen with just the proton is protium). Deuterium's nucleus, called a deuteron, is crucial to LCF.

As it stands, after billions of dollars of investment and decades of research, these approaches, which we'll call "hot fusion," still have a long way to go.

forming erbium into thulium or titanium into vanadium. Both kinds of stripping reactions would produce useful energy.

TO BE SURE THAT we were actually producing fusion in our vials of erbium deuteride and titanium deuteride, we used neutron spectroscopy. This technique detects the neutrons that result from fusion reactions. When deuteron-deuteron fusion produces a helium-3 nucleus and a neutron, that neutron has an energy of 2.45 MeV. So when we detected 2.45-MeV neutrons, we knew fusion had occurred. That's when we published our initial results in *Physical Review C.*

Electron screening makes it *seem* as though the deuterons are fusing at a temperature of 11 million °C. In reality, the metal lattice remains much cooler than that, although it heats up somewhat from room temperature as the deuterons fuse.

Overall, in LCF, most of the heating occurs in regions just tens of micrometers across. This is far more efficient than in magnetic- or inertial-confinement fusion reactors, which heat up the entire fuel amount to very high temperatures. LCF isn't cold fusion—it still requires energetic deuterons and can use neutrons to heat them. However, LCF also removes many of the technological and engineering barriers that have prevented other fusion schemes from being successful.

Although the neutron recoil technique we've been using is the most efficient means to transfer energy to cold deuterons, producing neutrons from a Dynamitron is energy intensive. There are other, lower-energy methods of producing neutrons, including using an isotopic neutron source, like americium-beryllium or californium-252, to initiate the reactions. We also need to make the reaction self-sustaining, which may be possible using neutron reflectors to bounce neutrons back into the lattice—carbon and beryllium are examples of common neutron reflectors. Another option is to couple a fusion neutron source with fission fuel to take advantage of the best of both worlds. Regardless, more work is required to increase the efficiency of these lattice-confined nuclear reactions.

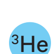
We've also triggered nuclear reactions by pumping deuterium gas through a thin wall of a palladium-silver alloy tubing, and by electrolytically loading palladium with deuterium. In the latter experiment, we've detected fast neutrons. The electrolytic setup is now using the same neutron-spectroscopy detection method we mentioned above to measure the energy of those neutrons. The energy measurements we get will inform us about the kinds of nuclear reaction that produce them.

We're not alone in these endeavors. Researchers at Lawrence Berkeley National Laboratory, in California, with funding from Google Research, achieved favorable results with a similar electron-screened fusion setup. Researchers at the U.S. Naval Surface Warfare Center, Indian Head Division, in Maryland, have likewise gotten promising initial results using an electrochemical approach to LCF. There are also upcoming conferences: the American Nuclear Society's Nuclear and Emerging Technologies for Space conference in Cleveland in May and the International Conference on Cold Fusion 24, focused on solid-state energy, in Mountain View, Calif., in July.

Any practical application of LCF will require efficient, self-sustaining reactions. Our work represents just the first step toward realizing that goal. If the reaction rates can be significantly boosted, LCF may open a brand new door for generating clean nuclear energy, both for space missions and for the many people who could use it here on Earth. ■

DEUTERON: The nucleus of a deuterium atom. Deuterons are vital to LCF—the actual fusion instances occur when an energetic deuteron smashes into another in the lattice. They can also be broken apart in stripping reactions.

HYDROGEN-3 (TRITIUM): One possible resulting particle from deuteron-deuteron fusion, alongside a leftover proton. Tritium has one proton and two neutrons in its nucleus, which is also called a triton.

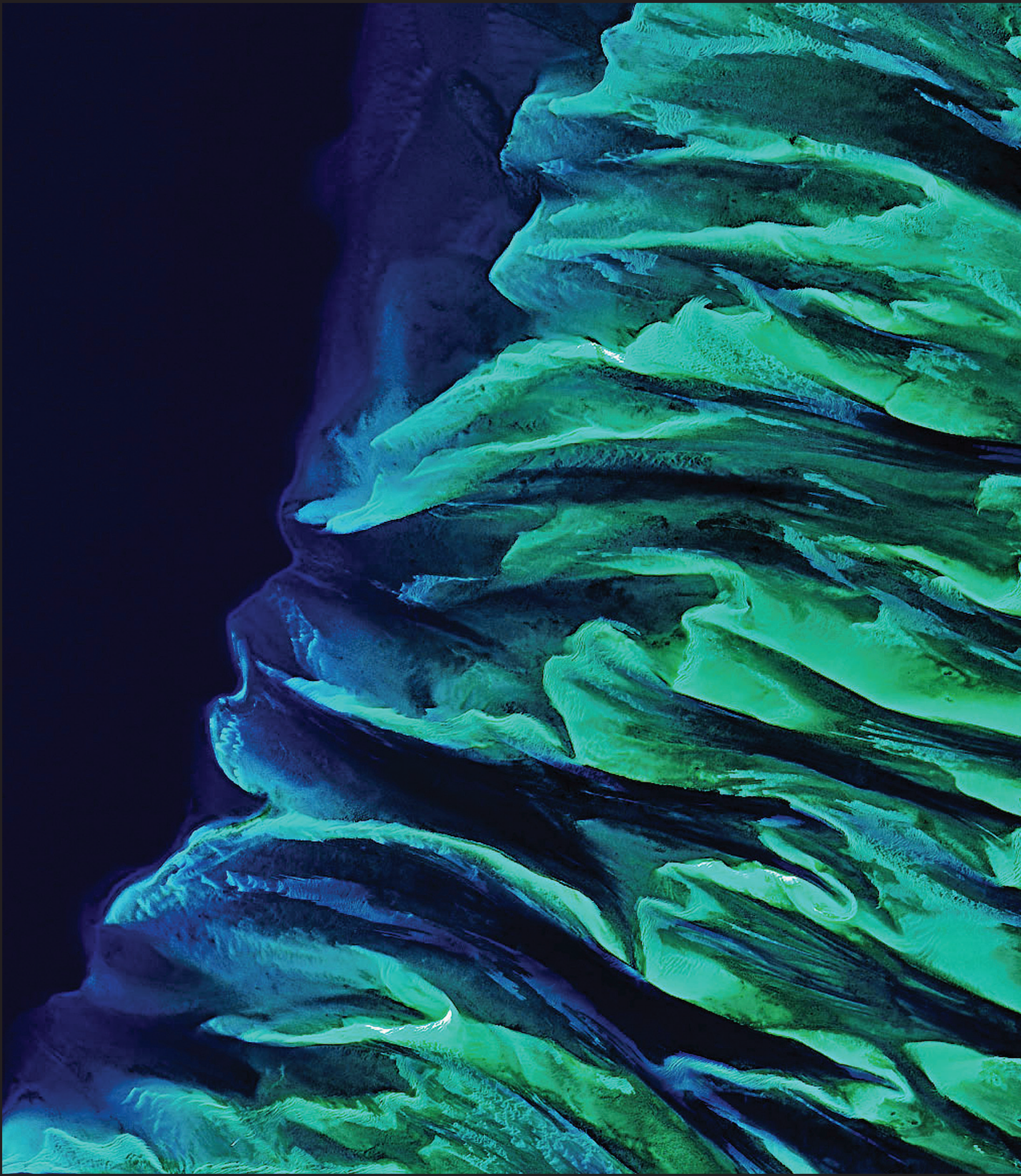


HELIUM-3: One possible resulting particle from deuteron-deuteron fusion, alongside a leftover neutron. Helium-3 has two protons and one neutron in its nucleus, which is also called a helion.

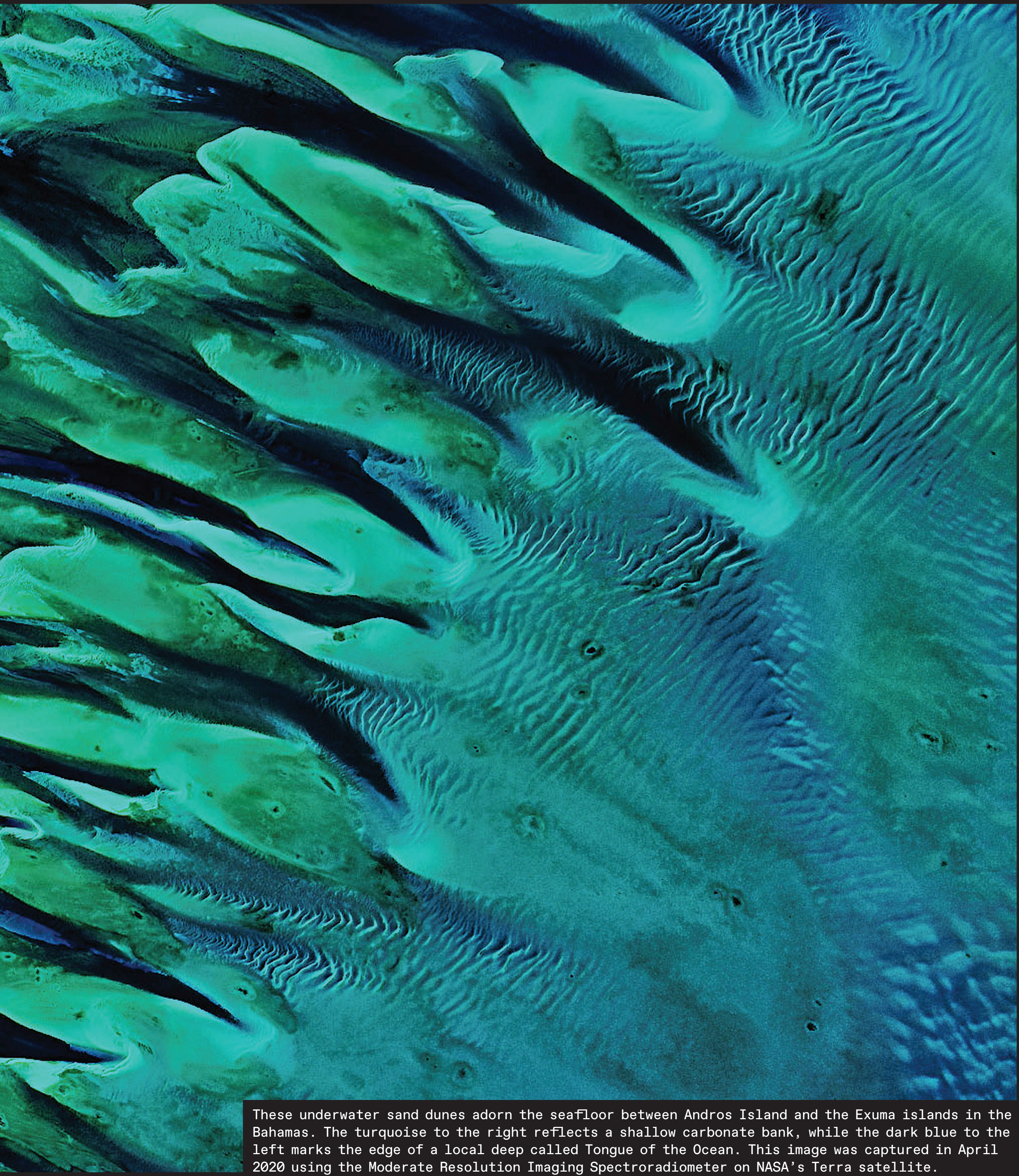
ALPHA PARTICLE: The core of a normal helium atom (two protons and two neutrons). Alpha particles are a common result of typical fusion reactors, which often smash deuterium and tritium particles together. They can also emerge from LCF reactions.

GAMMA RAY: Extremely energetic photons that are used to kick off the fusion reactions in a metal lattice by breaking apart deuterons.

A Boom With a View



The satellite-imaging industry is exploding. Here's how to take advantage of it **BY DEXTER JAGULA**



JOSHUA STEVENS/NASA EARTH OBSERVATORY

These underwater sand dunes adorn the seafloor between Andros Island and the Exuma islands in the Bahamas. The turquoise to the right reflects a shallow carbonate bank, while the dark blue to the left marks the edge of a local deep called Tongue of the Ocean. This image was captured in April 2020 using the Moderate Resolution Imaging Spectroradiometer on NASA's Terra satellite.

Every day, satellites circling overhead capture trillions of pixels of high-resolution imagery of the surface below. In the past, this kind of information was mostly reserved for specialists in government or the military. But these days, almost anyone can use it.

That's because the cost of sending payloads, including imaging satellites, into orbit has dropped drastically. High-resolution satellite images, which used to cost tens of thousands of dollars, now can be had for the price of a cup of coffee.

What's more, with the recent advances in artificial intelligence, companies can more easily extract the information they need from huge digital data sets, including ones composed of satellite images. Using such images to make business decisions on the fly might seem like science fiction, but it is already happening within some industries.

Here's a brief overview of how you, too, can access this kind of information and use it to your advantage. But before you'll be able to do that effectively, you need to learn a little about how modern satellite imagery works.

The orbits of Earth-observation satellites generally fall into one of two categories: GEO and LEO. The former is shorthand for geosynchronous equatorial orbit. GEO satellites are positioned roughly 36,000 kilometers above the equator, where they circle in sync with Earth's rotation. Viewed from the ground, these satellites appear to be stationary, in the sense that their bearing and elevation remain constant. That's why GEO is said to be a *geostationary* orbit.

Such orbits are, of course, great for communications relays—it's what allows people to mount satellite-TV dishes on their houses in a fixed orientation. But GEO satellites are also appropriate when you want to monitor some region of Earth by capturing images over time. Because the satellites are so high up, the resolution of that imagery is quite coarse, however. So these orbits are primarily used for observation satellites designed to track changing weather conditions over broad areas.

Being stationary with respect to Earth means that GEO satellites are always within range of a downlink station, so they can send data back to Earth in minutes. This allows them to alert people to changes in weather patterns almost in real time. Most of this kind of data is made available for free by the U.S. National Oceanographic and Atmospheric Administration.

The other option is LEO, which stands for low Earth orbit. Satellites placed in LEO are much closer to the ground, which allows them to obtain higher-resolution images. And the lower you can go, the better the resolution you can get. The company Planet, for example, increased the resolution of its recently completed satellite constellation, SkySat, from 72 centimeters per pixel to just 50 cm—an incredible feat—by lowering the orbits its satellites follow from 500 to 450 km and improving the image processing.

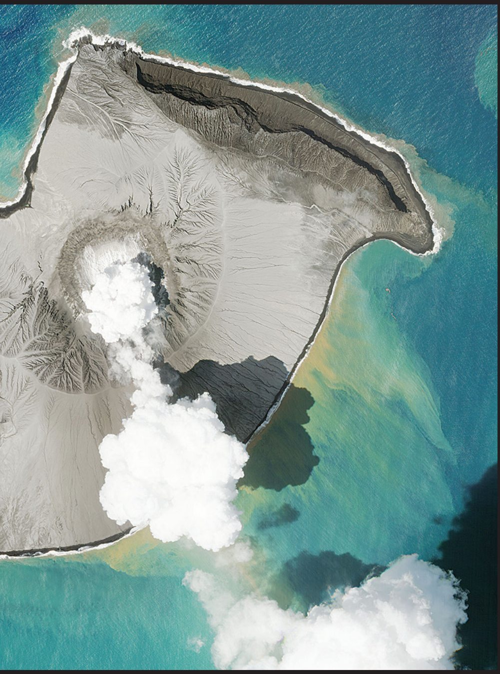
The best commercially available spatial resolution for optical imagery is 25 cm, which means that one pixel represents a 25-by-25-cm area on the ground—roughly the size of your laptop. A handful of companies capture data with 25-cm to 1-meter resolution, which is considered high to very high resolution in this industry. Some of these companies also offer data from 1- to 5-meter resolution, considered medium to high resolution. Finally, several government programs have made optical data available at 10-, 15-, 30-, and 250-meter resolutions for free with open data programs. These include NASA/U.S. Geological Survey Landsat, NASA MODIS (Moderate Resolution Imaging Spectroradiometer), and ESA Copernicus. This imagery is considered low resolution.

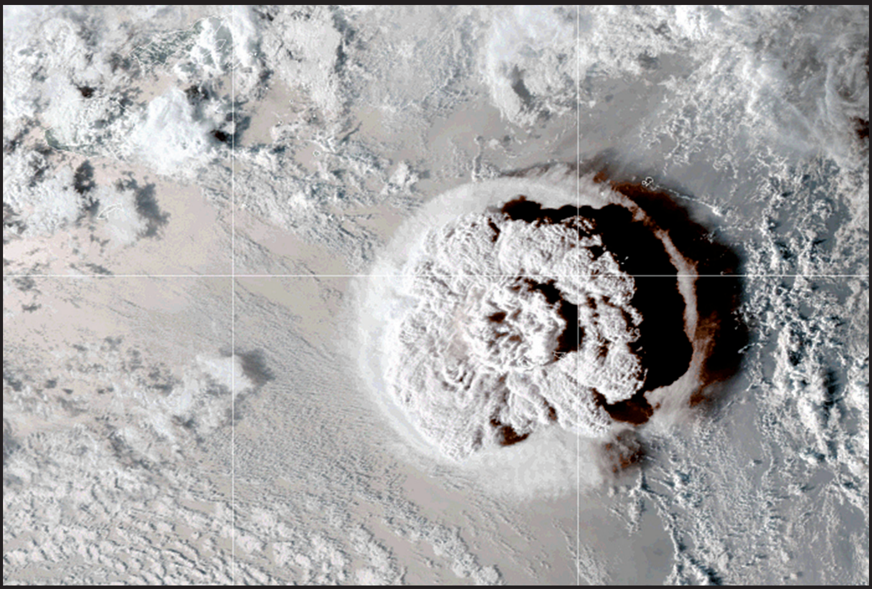
Because the satellites that provide the highest-resolution images are in the lowest orbits, they sense less area at once. To cover the entire planet, a satellite can be placed in a polar orbit, which takes it from pole to pole. As it travels, Earth rotates under it, so on its next pass, it will be above a different part of Earth.

Many of these satellites don't pass directly over the poles, though. Instead, they are placed in a near-polar orbit that

In March 2021, the container ship *Ever Given* ran aground, blocking the Suez Canal for six days. This satellite image of the scene, obtained using synthetic-aperture radar, shows the kind of resolution that is possible with this technology.

CAPELLA SPACE





On 15 January of this year, an immensely powerful volcanic eruption rocked an uninhabited island in the South Pacific known as Hunga Tonga-Hunga Ha'apai [left]. The massive eruption, which had far-reaching effects, was captured by NOAA's Geostationary Operational Environmental Satellite 17 [right].

LEFT: SKYSAT/PLANET; RIGHT: JOSHUA STEVENS AND LAUREN DAUPHIN/NOAA/NESDIS/NASA

has been specially designed to take advantage of a subtle bit of physics. You see, the spinning Earth bulges outward slightly at the equator. That extra mass causes the orbits of satellites that are not in polar orbits to shift or (technically speaking) to precess. Satellite operators often take advantage of this phenomenon to put a satellite in what's called a sun-synchronous orbit. Such orbits allow the repeated passes of the satellite over a given spot to take place at the same time of day. Not having the pattern of shadows shift between passes helps the people using these images to detect changes.

It usually takes 24 hours for a satellite in polar orbit to survey the entire surface of Earth. To image the whole world more frequently, satellite companies use multiple satellites, all equipped with the same sensor and following different orbits. In this way, these companies can provide more frequently updated images of a given location. For example, Maxar's Worldview Legion constellation, launched last year, includes six satellites.

After a satellite captures some number of images, all that data needs to be sent down to Earth and processed. The time required for that varies.

DigitalGlobe (which Maxar acquired in 2017) recently announced that it had managed to send data from a satellite down to a ground station and then store it in the cloud in less than a minute. That was possible because the image sent back was of the parking lot of the ground station, so the satellite didn't have to travel between the collection point and where it had to be to do the data "dumping," as this process is called.

In general, Earth-observation satellites in LEO don't capture imagery all the time—they do that only when they are above an area of special interest. That's because these satellites are limited to how much data they can send at one time. Typically, they can transmit data for only 10 minutes or so before they get out of range of a ground station. And they cannot record more data than they'll have time to dump.

Currently, ground stations are located mostly near the poles, the most visited areas in polar orbits. But we can soon expect distances to the nearest ground station to shorten because both Amazon and Microsoft have announced intentions to build large networks of ground stations located all over the world. As it turns out, hosting the terabytes of satellite data that are collected daily is big business for these companies, which sell their cloud services (Amazon Web Services and Microsoft's Azure) to satellite operators.

For now, if you are looking for imagery of an area far from a ground station, expect a significant delay—maybe hours—between capture and transmission of the data. The data will then have to be processed, which adds yet more time. The fastest providers currently make their data available within 48 hours of capture, but not all can manage that. While it is possible, under ideal weather conditions, for a commercial entity to request a new capture and get the data it needs delivered the same week, such quick turnaround times are still considered cutting edge.

I've been using the word "imagery," but it's important to note that satellites do not capture images the same way ordinary cameras do. The optical sensors in satellites are calibrated to measure reflectance over specific bands of the electromagnetic spectrum. This could mean they record how much red, green, and blue light is reflected from different parts of the ground. The satellite operator will then apply a variety of adjustments to correct colors, combine adjacent images, and account for parallax, forming what's called a true-color composite image, which looks pretty much like what you would expect to get from a good camera floating high in the sky and pointed directly down.

Imaging satellites can also capture data outside of the visible-light spectrum. The near-infrared band is widely used in agriculture, for example, because these images help farmers gauge the health of their crops. This band can also be used to detect soil moisture and a variety of other ground features that would otherwise be hard to determine.

Longer-wavelength "thermal" IR does a good job of penetrating smoke and picking up heat sources, making it useful for wildfire monitoring. And synthetic-aperture radar satellites, which I discuss in greater detail below, are becoming more common because the images they produce aren't affected by clouds and don't require the sun for illumination.

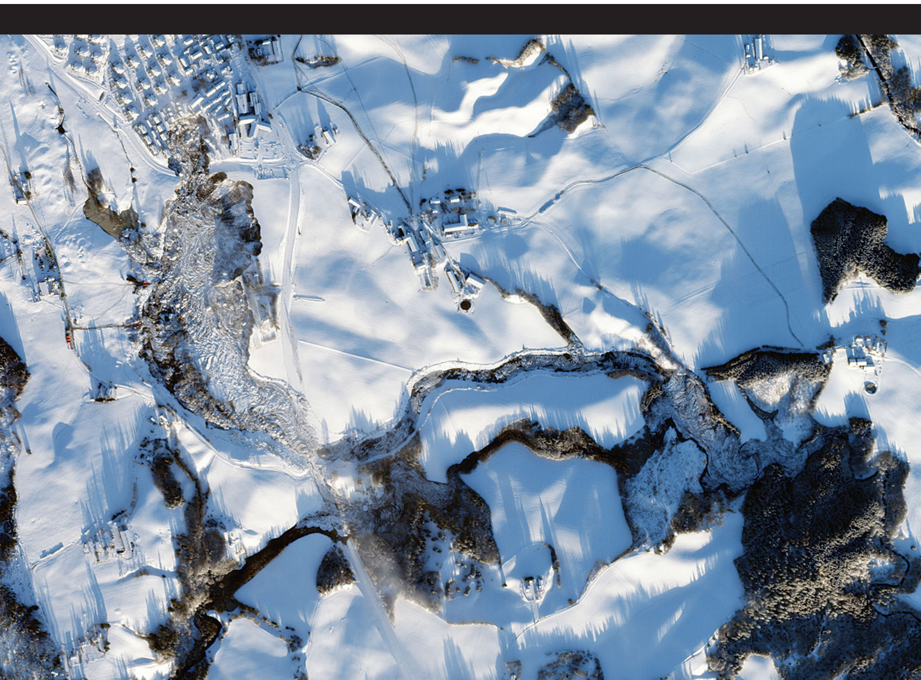
You might wonder whether aerial imagery, say, from a drone, wouldn't work at least as well as satellite data. Sometimes it can. But for many situations, using satellites is the better strategy. Satellites can capture imagery over areas that would be difficult to access otherwise because of their remoteness, for example. Or there could be other sorts of accessibility issues: The area of interest could be in a conflict zone, on private land, or in another place that planes or drones cannot overfly.

So with satellites, organizations can easily monitor the changes taking place at various far-flung locations. Satellite imagery allows pipeline operators, for instance, to quickly identify incursions into their right-of-way zones. The company can then take steps to prevent a disastrous incident, such as someone puncturing a gas pipeline while construction is taking place nearby.

The ability to compare archived imagery with recently acquired data has helped a variety of industries. For example, insurance companies sometimes use satellite data to detect fraudulent claims ("Looks like your house had a damaged roof when you bought it…"). And financial-investment firms use satellite imagery to evaluate such things as retailers' future profits based on parking-lot fullness or to predict crop prices before farmers report their yields for the season.

Satellite imagery provides a particularly useful way to find or monitor the location of undisclosed features or activities. Sarah Parcak of the University of Alabama, for example, uses satellite imagery to locate archaeological sites of interest. 52Impact, a consulting company in the Netherlands, identified undisclosed waste dump sites by training an algorithm to recognize their telltale spectral signature. Satellite imagery has also helped identify illegal fishing activities, fight human trafficking, monitor oil spills, get accurate reporting on COVID-19 deaths, and even investigate Uyghur internment camps in China—all situations where the primary actors couldn't be trusted to accurately report what's going on.

Despite these many successes, investigative reporters and nongovernmental organizations aren't yet using satellite data regularly, perhaps because even the small cost of the imagery is a deterrent. Thankfully, some kinds of low-resolution satellite data can be had for free.



This SkySat image shows the effect of a devastating landslide that took place on 30 December 2020. Debris from that landslide destroyed buildings and killed 10 people in the Norwegian village of Ask.

SKYSAT/PLANET

T**he first place** to look for free satellite imagery is the Copernicus Open Access Hub and EarthExplorer. Both offer free access to a wide range of open data. The imagery is lower resolution than what you can purchase, but if the limited resolution meets your needs, why spend money?

If you require medium- or high-resolution data, you might be able to buy it directly from the relevant satellite operator. This field recently went through a period of mergers and acquisitions, leaving only a handful of providers, the big three in the West being Maxar and Planet in the United States and Airbus in Germany. There are also a few large Asian providers, such as SI Imaging Services in South Korea and Twenty First Century Aerospace Technology in Singapore. Most providers have a commercial branch, but they primarily target government buyers. And they often require large minimum purchases, which is unhelpful to companies looking to monitor hundreds of locations or fewer.

Fortunately, approaching a satellite operator isn't the only option. In the past five years, a cottage industry of consultants and local resellers with exclusive deals to service a certain market has sprung up. Aggregators and resellers spend years negotiating contracts with multiple providers so they can offer customers access to data sets at more attractive prices, sometimes for as little as a few dollars per image. Some companies providing geographic information systems—including Esri, L3Harris, and Safe Software—have also negotiated reselling agreements with satellite-image providers.

Traditional resellers are middlemen who will connect you with a salesperson to discuss your needs, obtain quotes from providers on your behalf, and negotiate pricing and priority schedules for image capture and sometimes also for the processing of the data. This is the case for Apollo Mapping, European

Space Imaging, Geocento, LandInfo, Satellite Imaging Corp., and many more. The more innovative resellers will give you access to digital platforms where you can check whether an image you need is available from a certain archive and then order it. Examples include LandViewer from EOS and Image Hunter from Apollo Mapping.

More recently, a new crop of aggregators began offering customers the ability to programmatically access Earth-observation data sets. These companies work best for people looking to integrate such data into their own applications or workflows. These include the company I work for, SkyWatch, which provides such a service, called EarthCache. Other examples are UP42 from Airbus and Sentinel Hub from Sinergise.

While you will still need to talk with a sales rep to activate your account—most often to verify you will use the data in ways that fits the company's terms of service and licensing agreements—once you've been granted access to their applications, you will be able to programmatically order archive data from one or multiple providers. SkyWatch is, however, the only aggregator allowing users to programmatically request future data to be collected ("tasking a satellite").

Satellite images have helped to reveal China's treatment of its Muslim Uyghur minority. About a million Uyghurs (and other ethnic minorities) have been interned in prisons or camps like the one shown here [top], which lies to the east of the city of Ürümqi, the capital of China's Xinjiang Uyghur Autonomous Region. Another satellite image [bottom] shows the characteristic oval shape of a fixed-chimney Bull's trench kiln, a type widely used for manufacturing bricks in southern Asia. This one is located in Pakistan's Punjab province. This design poses environmental concerns because of the sooty air pollution it generates, and such kilns have also been associated with human-rights abuses.

TOP: CNES/AIRBUS/GOOGLE EARTH; BOTTOM: MAXAR TECHNOLOGIES/GOOGLE EARTH

While satellite imagery is fantastically abundant and easy to access today, two changes are afoot that will expand further what you can do with satellite data: faster revisits and greater use of synthetic-aperture radar (SAR).

The first of these developments is not surprising. As more Earth-observation satellites are put into orbit, more images will be taken, more often. So how frequently a given area is imaged by a satellite will increase. Right now, that's typically two or three times a week. Expect the revisit rate soon to become several times a day. This won't entirely address the challenge of clouds obscuring what you want to view, but it will help.

The second development is more subtle. Data from the two satellites of the European Space Agency's Sentinel-1 SAR mission, available at no cost, has enabled companies to dabble in SAR over the last few years.

With SAR, the satellite beams radio waves down and measures the return signals bouncing off the surface. It does that continually, and clever processing is used to turn that data into images. The use of radio allows these satellites to see through clouds and to collect measurements day and night. Depending on the radar band that's employed, SAR imagery can be used to judge material properties, moisture content, precise movements, and elevation.

As more companies get familiar with such data sets, there will no doubt be a growing demand for satellite SAR imagery, which has been widely used by the military since the 1970s. But it's just now starting to appear in commercial products. You can expect those offerings to grow dramatically, though.

Indeed, a large portion of the money being invested in this industry is currently going to fund large SAR constellations, including those of Capella Space, Iceye, Synspective, XpressSAR, and others. The market is going to get crowded fast, which is great news for customers. It means they will be able to obtain high-resolution SAR images of the place they're interested in, taken every hour (or less), day or night, cloudy or clear.

People will no doubt figure out wonderful new ways to employ this information, so the more folks who have access to it, the better. This is something my colleagues at SkyWatch and I deeply believe, and it's why we've made it our mission to help democratize access to satellite imagery.

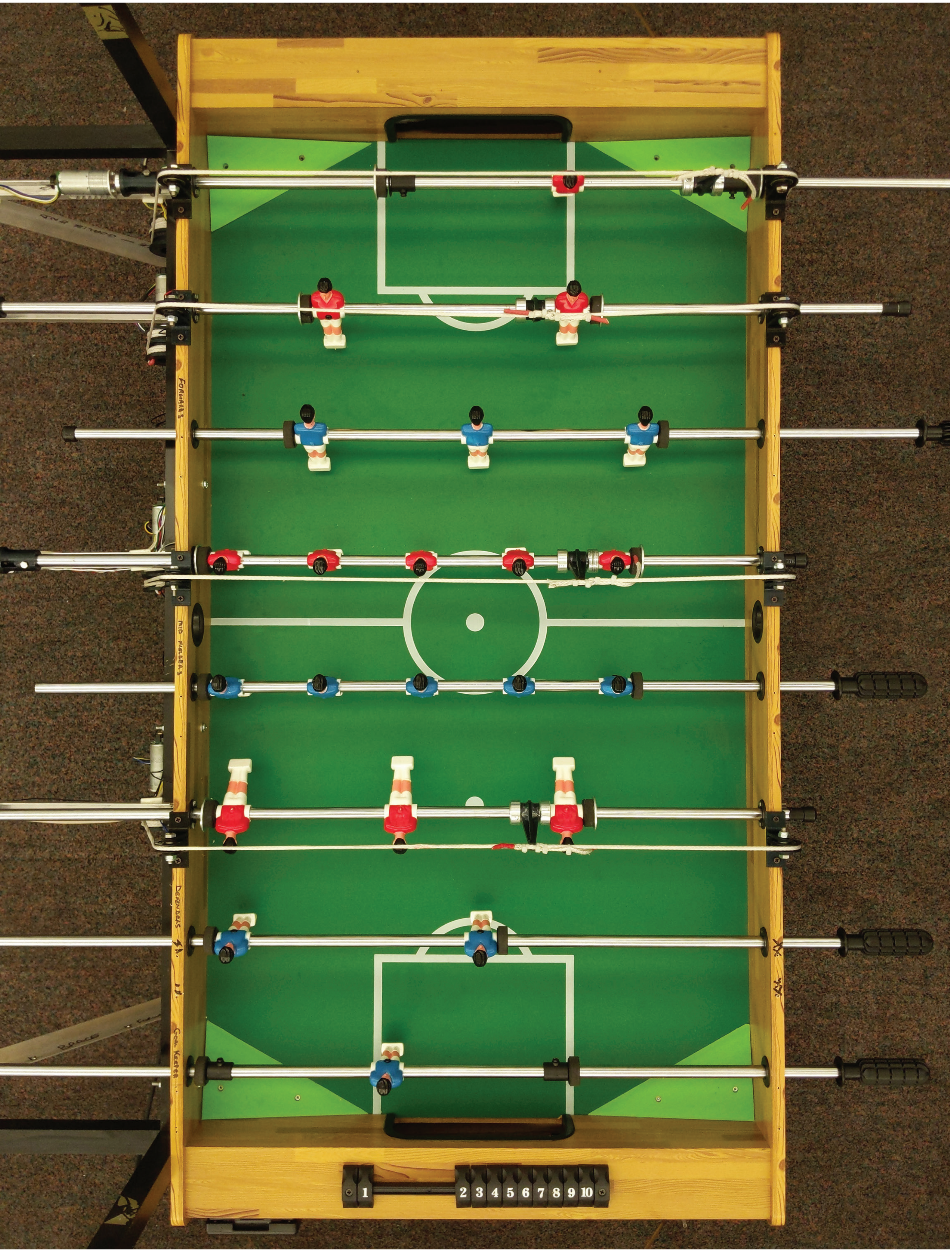
One day in the not-so-distant future, Earth-observation satellite data might become as ubiquitous as GPS, another satellite technology first used only by the military. Imagine, for example, being able to take out your phone and say something like, "Show me this morning's soil-moisture map for Grover's Corners High; I want to see whether the baseball fields are still soggy." ■

This robot foosball table is meant to serve as a benchmark test for neuromorphic algorithms and other technologies.

GOOAALL!!!

WHY WE BUILT A NEUROMORPHIC ROBOT TO PLAY FOOSBALL

BY GREGORY COHEN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PREVIOUS PAGE AND THIS SPREAD: WESTERN SYDNEY UNIVERSITY

FOR THE PAST 25 YEARS or so, those of us who seek to mimic the brain's workings in silicon have held an annual workshop in the mountain town of Telluride, Colo. During those summer weeks, you can often find the participants unwinding at the bar of the New Sheridan Hotel on the town's main street. As far back as most can remember, there has been a foosball table in the bar's back room. During the weeks of the workshop, you'll usually find it surrounded by a cluster of neuromorphic engineers engaged in a friendly rivalry that has spanned many years. It was therefore almost a foregone conclusion that someone was going to build a neuromorphic-robot foosball table.

That someone was me.

It turns out there's more to the idea than simple fun. After all, why do we play competitive games like foosball? We are drawn to them for social reasons, but we also enjoy learning the mechanics and improving our performance. Games are how we boost our hand-eye coordination, tracking and predictive abilities, and strategic thinking. Those are all skills we want robots to have.

Humans have always been fascinated by the idea of machines playing our games. As far back as the late 18th century, the Mechanical Turk hoax enthralled and amazed audiences with its (fictitious) ability to beat humans at chess. But we were all just as amazed in 1997 when IBM's Deep Blue did it for real. Now, such triumphs are almost a regular occurrence, with DeepMind's AI systems first defeating a human champion at the board game Go, and then going on to victory with the video game *StarCraft II*. (An AI will probably have conquered another of your favorite games by the time you finish reading this.)

These feats of computing are pretty good measures of a system's abilities. But they fall short in some important ways. Robots need to operate in a real world full of noise, irregularities, and evolving environments. The rigid rules and constrained environment of Go will never provide such challenges. Real-world games, certainly foosball and possibly pinball, might be a better measure of whether our efforts to match the might of the human brain are really on track.

Why are we so interested in learning biology's computational and sensing secrets? Frankly, it's because they are so superior to today's computing technology, which seems to be fast reaching its limits. Commodity sensors produce too much data for computers to understand, and those computers consume too much power trying to make sense of it. Biology outperforms all our technologies when it comes to sensing and perceiving the world, and biological organisms are orders of magnitude more power efficient, reliable, robust, and adaptable.

My colleague at Western Sydney University's International Centre for Neuromorphic Systems (ICNS), André van Schaik, gives a great example: the humble mosquito. Its brain is composed of only about 200,000 neurons, yet its flight control and obstacle avoidance are far superior to anything that we have built. Next, consider the dragonfly, which can capture a mosquito midflight. It has about five times as many neurons as the mosquito and consumes perhaps 30 mosquitoes' worth of energy per day,

about equivalent to a few grains of sugar.

One of the most straightforward examples of how neuromorphic technology can be used in sensing is vision, which happens to be my speciality. When it comes to building devices that need to see the world, cameras with CMOS imagers are almost always used. These cameras are such a commodity that it's easy to forget that a picture (which computer-vision researchers call a frame) is not the only way to perceive the visual world.

Cameras are built to capture a representation of a scene that's good enough to fool our visual system. We don't really know what features or information the visual system is using to understand the scene, so cameras simply capture as much information as possible. That approach is fine for taking static pictures, but it's not a great fit for doing things like tracking objects through space. For example, imagine trying to track an object—a foosball ball, for instance—that's moving so fast it completely leaves the edge of the image in the 33 milliseconds between one frame and another. Sure, you could use a camera with double the frame rate, but that means you've now got twice as much data to sort through just to keep track of that one object.

Biological eyes work differently. There are no frames in biology, and there are too few nerves going between the eyes and the brain to transmit whole images anyway. Neuromorphic vision sensors draw inspiration from how the eye's photoreceptors work; they still use lenses to project the world onto a grid of pixels on a silicon chip, but it's what those pixels do with the information that's interesting.

The pixels in neuromorphic sensors—also called event-based imagers—report only changes in illumination and only in the instant when the changes happen. They don't produce any data when nothing is changing in front of them. This approach drastically reduces the amount of data these cameras generate, which means less data to store, to transmit, and to process. These imagers therefore use less power both in the camera itself and for all the computation that needs to happen afterward.

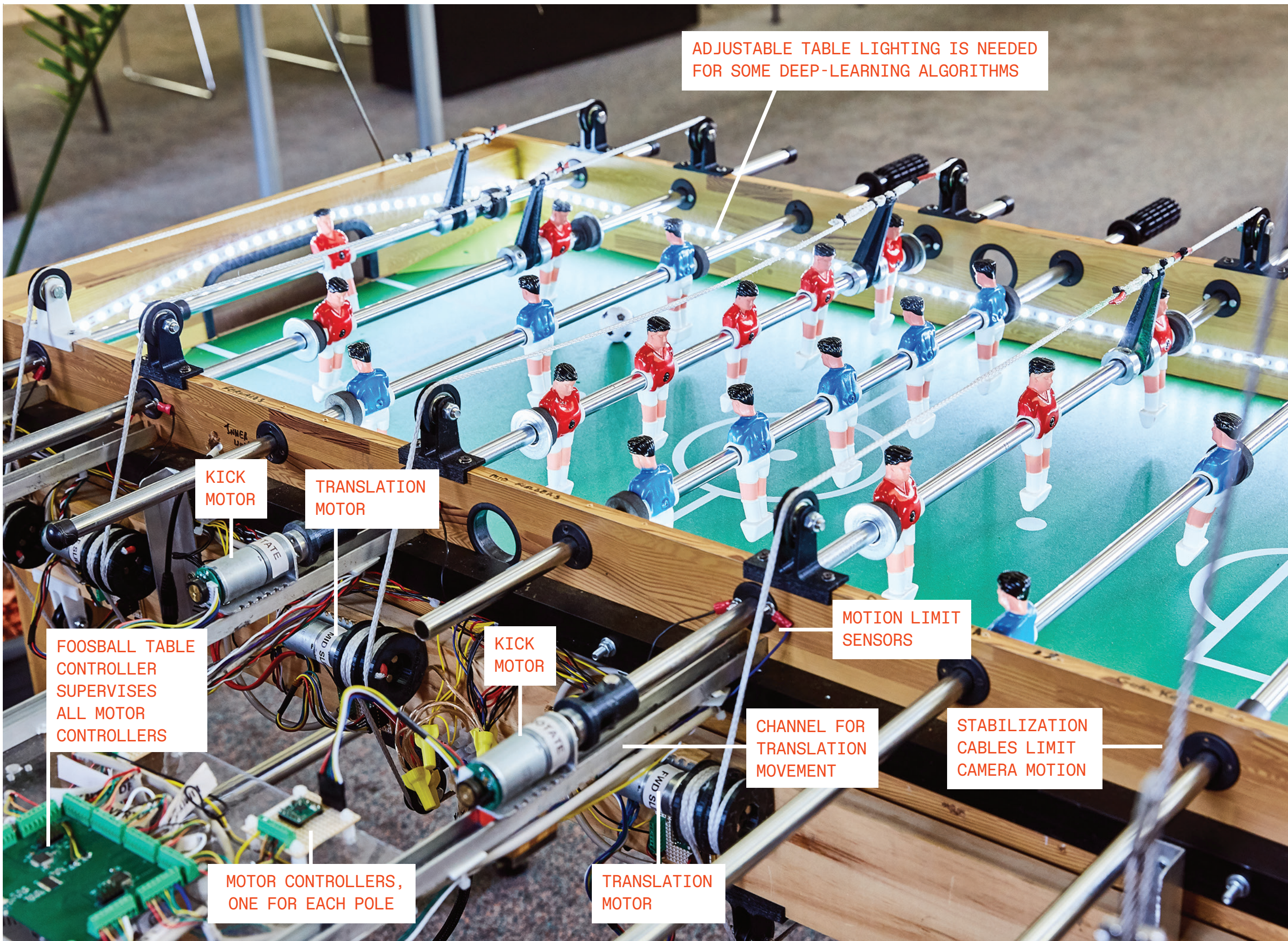
Startups Prophesee and IniVation already have brands of event-based imagers on the market. And these sensors have even gone to space: Neuromorphic cameras from ICNS will spot satellites and space junk from orbit, and a different sensor was recently installed on the International Space Station to examine ephemeral atmospheric phenomena, such as sprites.

Neuromorphic researchers have also tackled our other senses. They've developed silicon cochleas to model hearing, tactomorphic sensors to explore touch, and even a silicon nose to identify odors and gases. Beyond sensing, neuromorphic engineering seeks to understand the fundamental ways in which brains process and store information. In fact, the origins of neuromorphic engineering lie in trying to build electronic neurons to better understand how real neurons in the brain operate.

Neuromorphic sensors, and the brain-inspired algorithms that work with the data they produce, allow for specialized systems built specifically for efficient performance on certain tasks. However, it can be difficult to know when these sensors are capturing the right information or when our algorithms are working properly. That's where the need for benchmarks comes into play.

Left: Neuromorphic-robot foosball was born from neuromorphic engineers playing at the New Sheridan Hotel in Telluride.

Right: In its two trips to the Telluride Neuromorphic Cognition Engineering Workshop, our robot foosball table has seen plenty of use.



We designed the neuromorphic-robot foosball table to be easy to assemble, so other groups could make their own. Motors at the end of the rods rotate the players for kicking. A separate set of motors and pulleys slide the players across the table. Controllers orchestrate the motion according to the output of a neuromorphic algorithm.

WESTERN SYDNEY UNIVERSITY

To help understand why we need foosball as a neuromorphic benchmark, take the example of how an event-based imager would handle a benchmark that today's deep-learning AIs deal with all the time, the MNIST database. MNIST (short for Modified National Institute of Standards and Technology) is like the "Hello, World!" of machine vision. Its data set of thousands of low-resolution images of handwritten numerals offers a baseline for how well an image-recognition neural network is working.

An event-based imager would momentarily see each MNIST numeral as it flashes in front of it. For such a sensor to continue to see the static numerals, either the camera must move or the digit must, and in a controlled way. Eyes do something similar: Their focus moves from point to point until the brain understands what it's seeing.

Creating data sets like MNIST that are a suitable test for neuromorphic systems is not trivial, and the truth is they're not very useful. The process of linking motion to imaging can be so dynamic that for anything but the most constrained tasks, the number of possibilities would be quite large. So how can we determine if neuromorphic systems are working, and how can we compare them to other approaches?

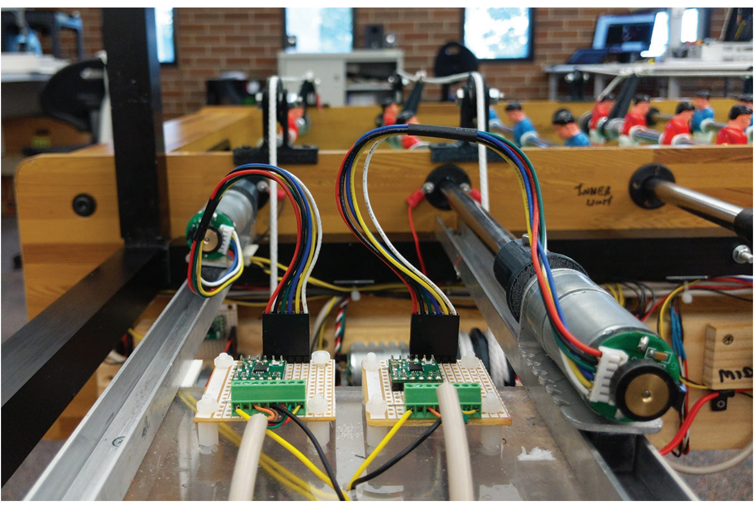
There are, of course, benchmarks that are interactive simulations. For example, in autonomous driving simulations, the view fed to the algorithm from the car's sensors changes as the car's position changes. But these simulations have their problems. The most significant is the contrast between controlling a simulation and controlling a physical system.

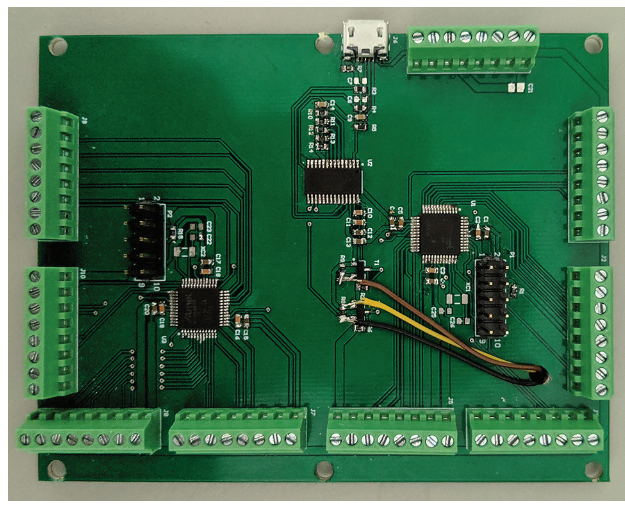
The major difference between simulated systems and reality lies in the amount and nature of noise in the real world. For most AI systems, noisy data is a big problem. But there's reason to believe that neuromorphic systems thrive with noise, and perhaps even need it. That's not as strange as it might seem. Our own sense of movement and body position is actually enhanced by a certain amount of noise. Attempts to mitigate noise in neuromorphic systems, either through extra pro-

Left: Like biological eyes, event-based cameras register only the changes in a scene. This greatly reduces the data needed for tracking the ball.

Below left: Each motor has its own controller.

Below right: The table control system supervises the motor controllers and performs other duties.





cessing or by designing real-world systems that are closer to our idealized simulations, may have held us back.

So what we need to move neuromorphic systems forward are benchmarks that are physically embedded in the real world.

Let's start with something simple: pinball. It's actually a very good choice for a benchmarking problem because the game is so straightforward. There are only two outputs, one for each flipper, and the game largely revolves around timing. The realities of the physical system are unforgiving, and you cannot simply pause or slow the movement of the ball to allow an algorithm to catch up. Most important, there's a score in pinball and a clear objective to maximize that score. So whichever system gets the highest score at pinball is unequivocally the better robotic pinball algorithm.

We can also make the problem more difficult by tweaking the game a little. For example, we can add multiple balls at the same time, or even decoy balls or balls of a material that will behave differently on the pinball table. This allows us to include a wider range of tasks such as tracking, detecting, segmenting, and identifying the balls while still maintaining the score as the ultimate metric for success.

Our approach to building a robotic foosball table aims to re-create the same inputs as those experienced by a human player.

ICNS has built a demo using a robotic pinball machine that can keep three balls on the table with about the same effectiveness as a human player. Amazingly, unlike the hundreds of thousands or millions of artificial neurons found in common deep-learning-based systems, this tiny neuromorphic brain interprets and acts on the input from an event-based imager using just two artificial neurons.

P**inball is great,** but my team felt there was a need for a more complicated and demanding task to further push the neuromorphic research community. Also, we like playing foosball at the New Sheridan Hotel's bar.

Foosball looks like an easy game for robots: All the action happens in two dimensions, and it takes only eight motors to control all the little figures on the table. But it's much more difficult than it seems.

There have been a few attempts over the years at building a robotic foosball table with varying degrees of success, but none using neuromorphic sensors and algorithms. The prior robotic systems often needed to modify the game to give the robot an advantage. For example, the foosball table built by Brigham Young University made use of a color-segmented tracking algorithm and required that the ball be the only green object on the table. The robotic foosball table at École Polytechnique Fédérale de Lausanne (EPFL), in Switzerland, is impressive, but it simplifies the task dramatically by replacing the bottom of the foosball table with a transparent plastic sheet and letting the camera look up, thereby always providing an unobstructed view of the ball.

Our approach aims to re-create the same inputs as those experienced by a human player. The camera looks down on the table, giving it an obstructed view that's similar to what a human would have. And we use a regulation ball, not one with special markings or colors.

Pinball is a simple test of neuromorphic systems. It's so simple, in fact, that we built a two-artificial-neuron system that could keep three balls in play at once.

Our robotic foosball table has so far made two trips from Australia to the mountains of Colorado. For three weeks at a time, teams of fresh neuromorphic engineers have descended upon the problem with gusto, taking up the challenge of programming the table to achieve the highest score. The results highlighted the difficulties of the task and the shortfalls of conventional AI methods.

For one thing, tracking the ball with a neuromorphic sensor should be easy, and in the trivial case of the pinball machine, it clearly is. However, foosball is a more dynamic game, especially when a human player is involved. Human players each have different strategies, and their movements are not always logical or even necessary.

Attempts to use non-neuromorphic solutions, such as deep learning, led to a few interesting lessons. First, it became apparent that the way deep-learning neural networks are processed—usually on a GPU—is not well suited to this type of task. GPUs operate best on batches of images rather than a single frame at a time. This is a problem, because we don't care about where the ball was in the past, and we don't really even care about where the ball is at the moment; what we really care about is where it's going to be next. So the deep-learning solutions were processing a lot of unnecessary information.

Second, we found that the deep-learning methods were extremely sensitive to small variations in the problem. A slight shake of the camera, a bit of skew in the table from players pulling it in different directions, or even a shift in lighting conditions caused the elegant performance of deep-learning ball trackers to break down. It's likely that we could increase the amount of training to handle all these small deviations—there's a whole field of research devoted to building networks that are resilient to these sorts of things—but that would take many, many more games.

Our latest approaches look toward simpler and faster neuromorphic networks. These algorithms process every event—also called a "spike" in neuromorphic computing—from the camera and use them to update the estimation of the position of the ball.

Instead of deep learning's vast layers of neurons, these networks use 16 small pattern-recognition networks of 18 x 18 pixels each, so only 364 pixels are being considered at any point in the game. This makes them very fast and mostly accurate. And being fast is critically important, because event-driven algorithms need to keep up with the time-sensitive data being produced by the camera. Each event necessitates no more than some small and simple calculations. While this system doesn't pose much of a threat to an experienced player, our network's tracking has improved to the point where it can quite reliably block the ball. Goal scoring, however, is still a work in progress.

Deep learning could perform a similar operation, in principle, but it needs to look at the entire image, and it performs orders of magnitude more calculations for each layer of the network. Not only is this far more data than our system uses, but it also effectively turns the event-driven output back into frames.

Currently, our algorithm is trained offline from recorded event-based data. It uses a genetic algorithm—one that evolves toward an optimal solution—to both learn what the ball looks like and to create good estimates of where it will be next. The algorithm learns how to recognize the ball from the data itself, rather than through any coding on our part. It also learns from how the ball really moves, rather than our own expectation of it. These are both important points, as our preconceptions of a good model for the ball turned out to be very far from those that work well. We also found that our simulations and expectations for the motion of the ball were wildly off.

Our next step is to move our learning from offline training to real-time online learning, allowing the network to continuously learn and adapt while the game is in progress. Among other things, that may help with a sensitivity the system has now to the specific table it's trained on.

These event-driven algorithms are an intermediate step toward algorithms designed to work using so-called spike-based neuromorphic hardware. These brain-inspired processors, such as Intel's Loihi and BrainChip's Akida, encode information as the timing of spikes and are a natural fit with event-based sensors. Once we have stable spike-based algorithms, we'll be able to make improvements more quickly.

Hopefully, we won't be the only ones making these improvements. In designing the robot foosball table, we focused on keeping the costs down and made the entire project open source. With luck, other neuromorphic research groups will see enough value in having their own robot benchmarks. And if not, they'll be able to find us and our foosball table in Telluride later this year. ■

GREGORY COHEN

THE INSTITUTE

NEWS OF THE IEEE
VOLUME 46 / ISSUE 1

PSYONIC

With This Haptic Hand, Amputees Regain a Sense of Touch P. 64

IEEE Is Your Professional Home

DID YOU KNOW that IEEE is not just an organization of electrical and electronics engineers? We welcome all those who are interested in and want to contribute to our technological mission.

As the world's largest technical professional organization, IEEE has long been composed of engineers, scientists, technologists, practitioners, and entrepreneurs. Members are experts from the highest echelons of academia, industry, and government, and they work in every vital area of technology. For this reason, the organization is now referred to simply as IEEE—your professional home.

As your professional home, within IEEE one can find computer scientists as well as electrical, mechanical, and electronics engineers. One can also find physicists and biologists who use our technical literature in their daily work; entrepreneurs and marketers who build their businesses on our members' technologies; technicians who demonstrate their proficiency through their technical advances published in our journals; and teachers who share their knowledge of science and technology with their students through our educational offerings.

Although IEEE still honors its electrical engineering roots, during the past few decades, its fields of interest have expanded well beyond electrical and electronics engineering and computing into just about any area one can imagine.

As technologies and the industries that developed them have increasingly transcended national boundaries, IEEE has kept pace. It has continued to expand its global presence to enhance its excellence in delivering products and services to members, industries, and the public at large.

Over the years, I have volunteered my time and effort to make IEEE a better place for all of us. I started as a student member more than 36 years ago. I started volunteering with the IEEE Signal Processing Society. Eventually I went on to oversee all of IEEE's societies and councils as vice president, Technical Activities, and I served on the IEEE Board of Directors. However, I am also still a member, just like all of you. I continue to read IEEE journals, participate in conferences, and use IEEE standards, and I enjoy engaging with my local chapter.

I understand the issues many of you, my fellow members, are facing in your professional lives, whether it's getting your career started after graduation, excelling or struggling in your position in academia or industry, or leveraging the "gig economy" as an entrepreneur.

And though the days when a technologist could count on lifetime employment with a single company are long gone, IEEE can be your professional home base from the time you first join as a student member until retirement. IEEE offers the products, services, networking opportunities, and educational and professional development programs required for every stage of your career.

IEEE spans our members' entire professional life cycle—catering to those just thinking about engineering or science as a career, as well as those already studying, teaching, practicing, inventing, or advocating for technology.

IEEE also provides members with a strong sense of community and a worldwide network of personal connections that can help mentor and nurture your professional journey.

The future

Together with the IEEE Board of Directors, I began this year with a commitment to shaping the IEEE of the future and examining ways in which the organization can evolve

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LinkedIn: linkedin.com/showcase/ieeepresident

IEEE

to best meet the needs of all technical professionals in the years ahead. Many of the advances we will make this year will be driven by an emphasis on our long-term success—all with a clear focus on our Code of Ethics and member conduct activities, including our commitment to inclusion and diversity.

My plan to make IEEE your professional home includes improving our engagement with our members and audience, seeking out the next big opportunities for IEEE and our members, enhancing IEEE awards' prestige, guiding IEEE in playing a leading role in addressing the climate crisis, and preparing IEEE for a world full of demographic, technological, economic, and environmental changes.

As a nonprofit organization, IEEE's key impetuses are the promotion of technical excellence, thought leadership, and the facilitation of collaboration and networking—rather than amassing profits.

The essential roles of our organization have always been facilitating the exchange of knowledge, advancing the technical state of the art, promoting guidelines and standards for professional excellence, and raising public awareness and recognition of members' contributions.

I encourage all our members to be engaged, be involved, and be part of the drive to reaffirm awareness of IEEE as your professional home to all members and other technologists around the world. After all, IEEE is your professional home. Please take care of yourself and each other.

—K.J. RAY LIU
IEEE president and CEO

Please share your thoughts with me at president@ieee.org.

EDITOR'S NOTE

Innovations for the Underserved

Ensuring those who need technology have access to it

MANY IEEE MEMBERS start off their engineering career as interns, but few end up running the company. That's not the case with Natarajan "Chandra" Chandrasekaran. The senior member has risen through the ranks and is now the chairman of Tata Sons, in Mumbai, India, the holding company for the Tata Group.

His focus for the company is to have a positive impact on society. On page 54, he discusses his vision for using artificial intelligence, cloud computing, the Internet of Things, and other technologies to improve conditions for the underserved.

On page 61, read about *Alvin*, a U.S. human-operated submersible that changed the course of oceanography. Now an IEEE Milestone, the 58-year-old vessel is still operating today. Scientists have used *Alvin*—developed by a research team at Woods Hole Oceanographic Institution—to study the effects of pressure on seafloor microbes. It also has discovered hydrothermal vents that help regulate ocean chemistry and support ecosystems.

As a youngster, Member Aadeel Akhtar made a pledge that one day he would build affordable artificial limbs.

He fulfilled that promise in September when his startup, Psyonic, released the Ability Hand, the fastest bionic hand on the market and the only one with touch feedback [page 64]. The haptic hand contains pressure sensors on the index finger, pinky, and thumb. It functions almost like a regular hand.

Another member who has done groundbreaking work is this year's IEEE Medal of Honor recipient, Asad Madni [page 56]. The award recognizes his contributions to the development and commercialization of innovative sensing and systems technologies.

The Life Fellow's quartz microelectromechanical system, GyroChip, is the first MEMS-based gyroscope and inertial measurement unit for aerospace and automotive safety.

On page 58, meet the members who are running to be the 2023 IEEE president-elect. The Board-nominated candidates are Life Fellow Thomas Coughlin and Senior Members Kathleen Kramer and Maike Luiken. Life Fellow Kazuhiro Kosuge is seeking to be a petition candidate. Learn about some of the key deadlines in this year's election on page 66. Also on that page you'll find the results of the 2021 election.

Need to brush up on some of today's latest technologies? IEEE Educational Activities is offering courses on blockchain [page 60].

On page 63, learn about the IEEE standards that can be found in a variety of well-known medical devices used both at home and in hospitals.

The IEEE Standards Association is also working to bring Internet access to those living in rural communities. Its Connectivity and Telecom Practice group has released several videotaped interviews with industry professionals, researchers, and policymakers working on providing worldwide access [page 63].

—KATHY PRETZ
Editor in chief, *The Institute*

For updates about IEEE and its members, visit us at spectrum.ieee.org/the-institute

PROFILE

From Engineering Intern to Chairman of Tata

TATA SONS

Natarajan Chandrasekaran seeks tech solutions to social problems

BY KATHY PRETZ

THERE WAS A TIME when managing the family farm in India would have been Natarajan "Chandra" Chandrasekaran's path, but his love of computer programming derailed that plan. After returning home from the Coimbatore Institute of Technology with a bachelor's degree in applied sciences, Chandra (as he likes to be called) tried his hand at farming but quickly realized it was not for him.

His father—who had given up his own career as a lawyer to run the farm after *his* father died—encouraged Chandra to continue to pursue his passion for computers.

Today the IEEE senior member is chairman of Tata Sons, in Mumbai, India, the holding company for the Tata Group, which encompasses more than 30 businesses. They include chemical plants, consultancy services, hotels, and steel mills.

Chandra chairs the boards of several of the companies including Tata Motors, Tata Power, Tata Consultancy Services (TCS), and Tata Steel. The group employs more than 750,000 people around the world.

Chandra says the ability for his company to make a difference is the single most important thing to him.

"We make an impact on our employees, society, businesses, and—with our huge ecosystem—on the markets in which we operate," he says.

From engineering intern to manager

After graduating from Coimbatore, in the state of Tamil Nadu, Chandra returned to run his family's farm in Mohanur, located in the state's Namakkal District. After breaking the news to his father that he would rather be a computer programmer than a farmer, Chandra entered a three-year postgraduate degree program to study computer science and its applications at the state's Regional Engineering College in Tiruchirappalli (now the National Institute of Technology).

An internship was required during the last semester. Chandra applied for an opening at TCS, an IT services company, which at the time was an up-and-coming firm with about 500 employees. Two months into the internship, the company offered him a job as an engineer after he graduated. He started working for TCS in 1987 and has never left.

He rose through the ranks, switching from engineering to management. He has held senior-level positions in marketing and sales, and has helped TCS grow its business around the world, including in China, Eastern Europe, and Latin America.

In 2009 he was promoted to chief executive. He held that position until 2017, when he was appointed chairman of Tata Sons.

"The company gave me a lot of different roles, and as you do better then you get lucky," he says, laughing. "Most of the knowledge I picked up was on the job and by taking on different projects."

He learned management skills from coworkers as well as working with clients, he says.

"TCS not only has the smartest people working for it, but we also work with some of the best companies as clients," he says. "When you work with smart people, you learn. And when you work with demanding clients, you learn. Things rub off on you. My passion has always been to understand deeply what makes a difference to a customer."

Employer
Tata Sons
Title
Chairman
Member grade
Senior member
Alma mater
Coimbatore Institute of Technology

Giving back

With India's under-resourced health care system, Chandra says, he knew COVID-19 could have a devastating effect on the country. Since April 2020 the Tata Group, including its philanthropic trusts, has committed more than US $200 million for COVID-related activities. That money has been used in a variety of ways, including building hospitals and increasing the capacity of existing ones by setting up COVID-19 wards and intensive-care units.

Once COVID-19 vaccines became available, the group started a massive campaign to inoculate its employees and their families.

"Helping is in our DNA," Chandra says of the affiliate companies in the group. "All of our CEOs have a culture of doing good for society."

Chandra says he often is asked when business will return to normal after the pandemic. He says it won't.

"We are not going back; we are going forward," he says. "While many things about COVID have been negative, there are many positives. COVID has moved the world forward in multiple dimensions. Number one is digital adoption. Number two: Everyone now recognizes the importance of sustainability, because we experienced how much we can dramatically change things, like air quality, in a relatively short period of time—especially in India."

> "I believe very strongly that digital-physical integration is the way to solve societal problems."

Tech solutions

Chandra says artificial intelligence and related technologies can help mankind tackle societal issues such as universal access to health care and a quality education. He outlined his ideas in *Bridgital Nation: Solving Technology's People Problem*, a book he coauthored with Roopa Purushothaman.

"I believe very strongly that digital-physical integration is the way to solve problems," he says. "Take a country like India—we have a shortage of everything. We have a shortage of doctors, schools, hospitals, and infrastructure. We neither have the time nor the money to be able to build all the capacity we need."

For example, about two-thirds of India's citizens live in rural areas, he notes, but most of the doctors are in cities.

He says the solution is to use AI, machine learning, the Internet of Things, and cloud computing to create a network of services that can be delivered where they are needed most. That would include telehealth and remote learning for people in rural areas.

Poverty could be reduced dramatically, he says, by using AI to increase the capabilities of low-skilled workers so they could perform higher-level jobs. In 2019 the Tata Group unveiled the Indian Institute of Skills, a joint initiative with the Ministry of Skills Development and the Indian government that provides vocational training.

The top skill he says everyone should have is the ability to continue to learn. That's why he renews his IEEE membership, he says.

Chandra became a member in 1987 because TCS required its professional employees to join a society. His colleagues recommended IEEE because, they said, he would become more knowledgeable about engineering and cutting-edge technology by reading its publications.

He remains a member, he says with a laugh, "because I still have [much] to learn." ■

Medal of Honor Goes to Microsensor and Systems Pioneer

BY JOANNA GOODRICH

IEEE LIFE FELLOW Asad M. Madni is the recipient of this year's IEEE Medal of Honor, which is sponsored by the IEEE Foundation. He is being recognized "for pioneering contributions to the development and commercialization of innovative sensing and systems technologies, and for distinguished research leadership."

Madni has been a distinguished adjunct professor of electrical and computer engineering and a distinguished scientist since 2011 at the Samueli School of Engineering at the University of California, Los Angeles. He is also a faculty Fellow at the UCLA Institute of Transportation Studies and the university's Connected Autonomous Electric Vehicle Consortium.

UCLA SAMUELI SCHOOL OF ENGINEERING

Before starting his career in academia, Madni served as chairman, president, and chief executive of Systron Donner and president, chief operating officer, and chief technology officer of BEI.

Madni led the development and commercialization of intelligent microsensors and systems for the aerospace, defense, industrial, and transportation industries. The GyroChip technology he helped develop at BEI revolutionized navigation and stability in aerospace and automotive systems, making them safer.

While at BEI, he also led the development of an extremely slow motion servo control system for NASA's Hubble Space Telescope's star selector. The system, which is still used today, provided the telescope with unprecedented pointing accuracy and stability, allowing astronomers to make new discoveries and learn more about the universe's history.

Smart sensors

Under Madni's leadership, BEI's quartz rate sensor technology, later known as the GyroChip, was developed in the early 1990s. The technology is the first microelectromechanical system (MEMS)-based gyroscope and inertial measurement unit for aerospace and automotive safety applications, according to an entry about Madni on the Engineering and Technology History Wiki. It is smaller and more cost-efficient and reliable than prior technologies.

The GyroChip is used worldwide in more than 90 types of aircraft, including the stability control systems of the Boeing 777; the yaw damper for the Boeing 737; and in most business jets as a sensing element in altitude control and reference programs. It also is used for guidance, navigation, and control in major U.S. missiles, underwater autonomous vehicles, and helicopters, as well as NASA's Mars rover Sojourner and AERCam Sprint autonomous robotic camera.

The GyroChip is also employed in the U.S. Civil Air Patrol's Airborne Real-time Cueing Hyperspectral Enhanced Reconnaissance system, which is deployed in search-and-rescue missions.

Madni led the defense conversion of the GyroChip technology from the aerospace and defense sectors to the automotive and commercial aviation markets.

The GyroChip became the foundation of vehicle dynamic control, which monitors a driver's actions including braking and steering to combat the loss of steering control that can occur in unsafe driving conditions. The GyroChip is used in more than 80 models of passenger cars worldwide for electronic stability control and rollover protection.

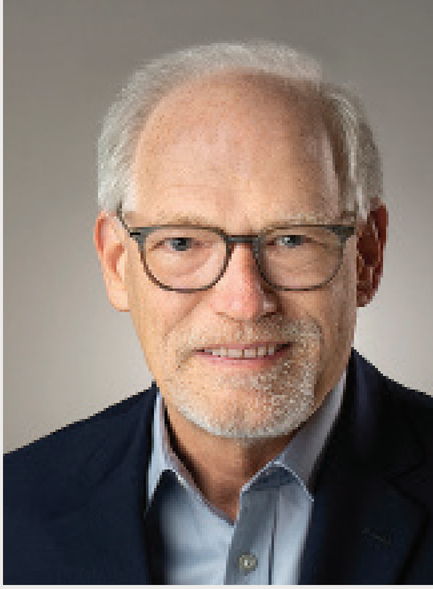
The GyroChip and numerous other sensing, actuation, and signal-processing techniques developed by Madni laid the foundation for autonomous vehicles. The technologies and techniques are used for features such as lane-change assist, autonomous cruise control, steering and wheel-speed detection, navigation, and drowsy- and drunken-driver detection.

While at Systron Donner, Madni led the development of RF and microwave systems and instrumentation—which significantly enhanced the combat readiness of the U.S. Navy and its allies. The technologies provided the U.S. Department of Defense with the ability to simulate more threats for warfare training that are representative of ECM environments. ■

IEEE ELECTION

Members Who Are Running for President-Elect

BY JOANNA GOODRICH



Thomas Coughlin

THE IEEE BOARD of Directors has nominated Life Fellow Thomas Coughlin and Senior Members Kathleen Kramer and Maike Luiken as candidates for IEEE president-elect. IEEE Life Fellow Kazuhiro Kosuge is seeking to be a petition candidate.

Other members who want to become a petition candidate still may do so by submitting their intention to elections@ieee.org by 8 April.

The winner of this year's election will serve as IEEE president in 2024.

For more information about the election, president-elect candidates, and the petition process, visit the IEEE election website (ieee.org/about/corporate/election).

Life Fellow Thomas Coughlin

NOMINATED BY THE IEEE BOARD OF DIRECTORS

Coughlin is founder and president of Coughlin Associates, in San Jose, Calif., which provides market and technology analysis as well as data storage, memory technology, and business consulting services. He has more than 40 years of experience in the data storage industry and has been a consultant for more than 20 years. He has been granted six patents.

Before starting his own company, Coughlin held senior leadership positions at Ampex, Micropolis, and SyQuest.

He is the author of *Digital Storage in Consumer Electronics: The Essential Guide*, which is in its second edition. He is a regular contributor on digital storage for the *Forbes* blog and other news outlets.

He was the 2019 IEEE-USA president as well as the 2015–2016 IEEE Region 6 director. He also was chair of the IEEE New Initiatives and Public Visibility committees. He was vice president of operations and planning for the IEEE Consumer Technology Society and served as general chair of the 2011 Sections Congress in San Francisco.

He is an active member of the IEEE Santa Clara Valley (Calif.) Section, which he chaired, and has been involved with several societies and standards groups, as well as the IEEE Future Directions Committee.

As a distinguished lecturer for the Consumer Technology Society and IEEE Student Activities, he has spoken on digital storage in consumer electronics, digital storage and memory for artificial intelligence, and how students can make IEEE their "professional home."

Coughlin is a member of the IEEE–Eta Kappa Nu (IEEE-HKN) honor society.

He has received several recognitions including the 2020 IEEE Member and Geographic Activities Leadership Award.

Coughlin is active in several other professional organizations including the Society of Motion Picture and Television Engineers and the Storage Networking Industry Association.

Senior Member Kathleen Kramer

NOMINATED BY THE IEEE BOARD OF DIRECTORS

Kramer is a professor of electrical engineering at the University of San Diego, where she served as chair of the EE department and director of engineering from 2004 to 2013. As director she provided academic leadership for all of the university's engineering programs.

Her areas of interest include multisensor data fusion, intelligent systems, and cybersecurity in aerospace systems. She has authored or co-authored more than 100 publications.

Kramer has worked for several companies including Bell Communications Research, Hewlett-Packard, and Viasat.

She served as the 2017–2018 director of IEEE Region 6 and was the 2019–2021 IEEE secretary. In that position, she chaired the IEEE Governance Committee and helped make major changes including centralizing ethics conduct reporting, strengthening processes to handle ethics and member conduct, and improving the process used to periodically review each of the individual committees and major boards of the IEEE.

She has held several leadership positions in the IEEE San Diego Section, including chair, secretary, and treasurer. Her first position with the section was advisor to the IEEE University of San Diego Student Branch.

Kramer is an active leader within the IEEE Aerospace and Electronic Systems Society. She currently heads its technical operations panel on cybersecurity. From 2016 to 2018 she served as vice president of education.

She is a distinguished lecturer for the society and has given talks on signal processing, multisensor data fusion, and neural systems.

Kramer serves as an IEEE commissioner within ABET, the global accrediting organization for academic programs in applied


Kathleen Kramer


Maike Luiken


Kazuhiro Kosuge

science, computing, engineering, and technology. She has contributed to several advances for graduate programs, cybersecurity, mechatronics, and robotics.

Senior Member Maike Luiken

NOMINATED BY THE IEEE BOARD OF DIRECTORS

Luiken's career in academia spans 30 years, and she has more than 20 years of experience in industry. She is co-owner of Carbovate Development, in Sarnia, Ont., Canada, and is managing director of its R&D department. She also is an adjunct research professor at Western University in London, also in Ontario.

Her areas of interest include power and energy, information and communications technology, how progress in one field enables advances in other disciplines and sectors, and how the deployment of technologies contributes—or doesn't contribute—to sustainable development.

In 2001 she joined the National Capital Institute of Telecommunications in Ottawa as vice president of research alliances. There she was responsible for a wide area test network and its upgrades. While at the company, she founded two research alliance networks that spanned across industry, business, government, and academia in the areas of wireless and photonics.

She joined Lambton College, in Sarnia, in 2005 and served as dean of its School of Technology and Applied Research and Innovation, as well as Sustainability college-wide. Luiken led the expansion of applied research from a few projects to Lambton's becoming one of the top three research colleges in Canada in recent years.

In 2013 she founded the Bluewater Technology Access Centre (now the Lambton Manufacturing Innovation Centre). It provides applied research services to industry while offering students and faculty opportunities to develop solutions for industry problems.

Luiken, an IEEE-HKN member, was last year's vice president of IEEE Member and Geographic Activities. She was president of IEEE Canada in 2018 and 2019, when she also served as Region 7 director.

She has served on numerous IEEE boards and committees including the IEEE Board of Directors, the Canadian Foundation, Member and Geographic Activities, and the Internet Initiative.

Life Fellow Kazuhiro Kosuge

SEEKING PETITION CANDIDACY

Kosuge is seeking to be a petition candidate. You can sign his petition at ieee.org/petition.

Kosuge is a professor of robotic systems at the University of Hong Kong's electrical and electronic engineering department. He has been conducting robotics research for more than 35 years, has published more than 390 technical papers, and has been granted more than 70 patents.

He began his engineering career as a research staff member in the production engineering department of Japanese automotive manufacturer Denso. After two years, he joined the Tokyo Institute of Technology's department of control engineering as a research associate. In 1989 and 1990, he was a visiting research scientist at MIT.

After he returned to Japan, he began his academic career at Nagoya University as an associate professor.

In 1995 Kosuge left Nagoya and joined Tohoku University, in Sendai, Japan, as a faculty member in the machine intelligence and system engineering department. He is currently director of the university's Transformative AI and Robotics International Research Center.

An IEEE-HKN member, he has held several IEEE leadership positions including 2020 vice president of Technical Activities, 2015–2016 Division X director, and 2010–2011 president of the Robotics and Automation Society.

He has served in several advisory roles for Japan, including science advisor to the Ministry of Education, Culture, Sports, Science, and Technology's Research Promotion Bureau from 2010 to 2014. He was a senior program officer of the Japan Society for the Promotion of Science from 2007 to 2010. From 2005 to 2012, he served as a specially appointed Fellow of the Japan Science and Technology Agency's Center for Research and Development Strategy.

Among his honors and awards are the purple-ribbon Medal of Honor in 2018 from the emperor of Japan. ■

FROM LEFT: HARRY WHO PHOTOGRAPHY; JT MACMILLAN; HEATHER O'NEIL/PHOTOS UNLIMITED; MAJESTY PROFESSIONAL PHOTO

IEEE PRODUCTS

Brush Up On Blockchain

BY JOHANNA PEREZ

BLOCKCHAIN TECHNOLOGY IS often mentioned when speaking of cryptocurrencies. But, it also affects the supply chain, the Internet of Things, health care, and a number of other industries.

One of the key benefits of blockchain technology is decentralization—its ability to distribute data and computing power across multiple computers in an organization's network—according to a Yahoo Finance article.

"As blockchain technology continues to evolve and expand into business sectors, organizations must understand how to properly integrate it into their systems," says course author Hunter Albright, IEEE member and co-chair for both the IEEE Blockchain Initiative and its blockchain-enabled transactive energy work.

IEEE Educational Activities and the IEEE Blockchain Initiative have partnered to create a five-course program, A Step-by-Step Approach to Designing Blockchain Solutions. It offers guidance to help product managers, designers, architects, and other technical professionals who need to understand the expected benefits and costs of blockchain solutions.

Individuals who complete the course program can earn up to 0.5 continuing-education units or 5 professional development hour credits, plus a digital badge.

The five courses are:

Making the Case

Learn the basics of blockchain solutions in this course, which includes an overview of the connection between the technology and business operations.

Defining Functional Requirements

This course covers the ecosystem and key elements. Learn how to define, specify, and determine performance requirements and government requirements.

Defining Non-Functional Requirements

This class explores the layers of blockchain technology.

Selecting the Platform

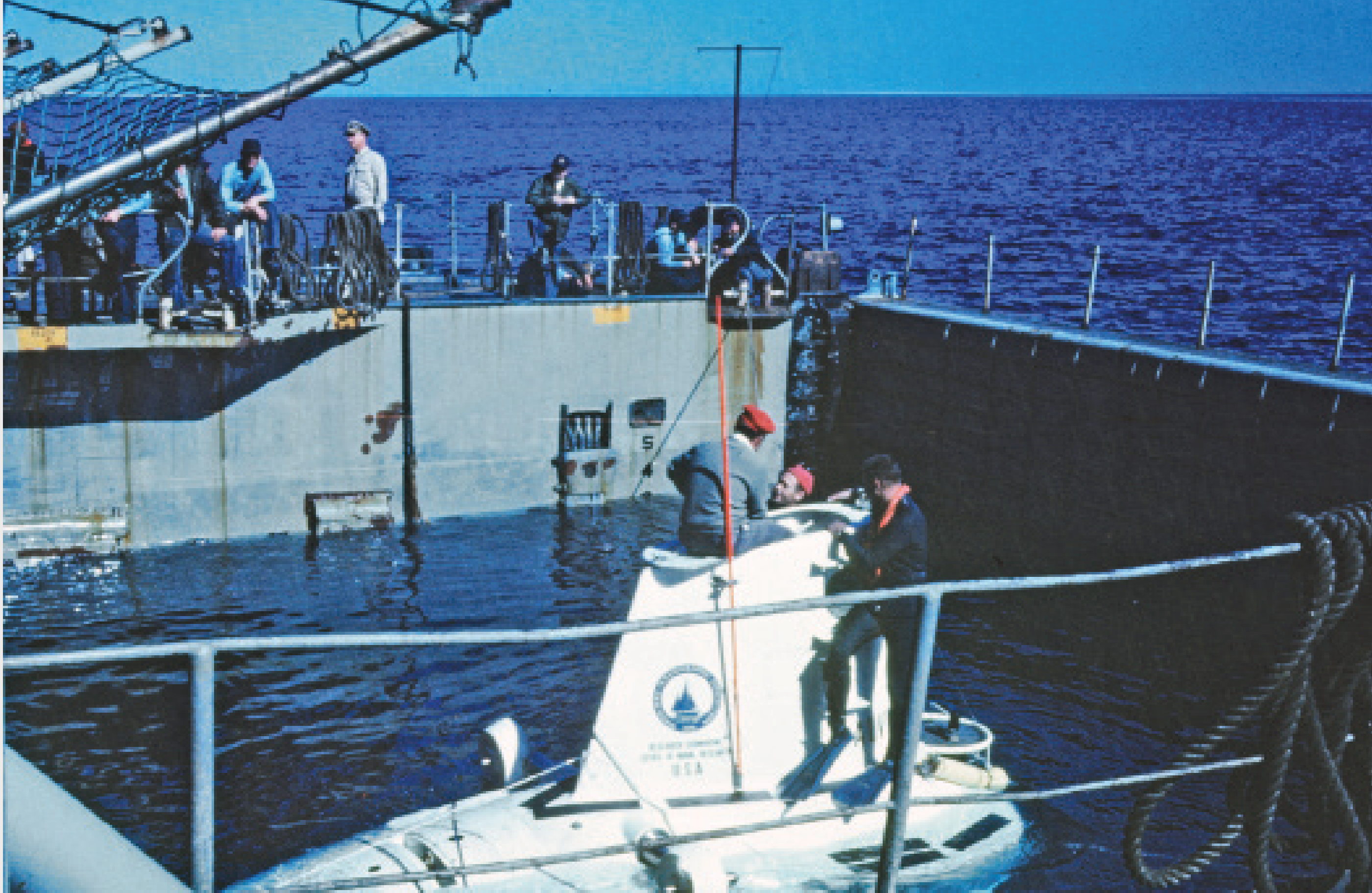
Learn how to choose the right solution. This course covers key platform considerations and provides insights on whether to build, buy, or partner.

Implementing the Solution

The resources in this class can help you avoid common mistakes made in implementing the technology.

Visit the IEEE Learning Network for member and nonmember pricing.

Johanna Perez is a digital marketing specialist for IEEE Educational Activities.



Woods Hole Oceanographic Institution's *Alvin* submersible being prepared for a dive.

WOODS HOLE OCEANOGRAPHIC INSTITUTION

TECH HISTORY

After 58 Years, *Alvin* Still Explores the Ocean Depths

The U.S. crewed submersible has been honored with an IEEE Milestone

BY JOANNA GOODRICH

WATER PRESSURE in the deep sea makes human exploration of the ocean difficult. Special equipment such as a scuba regulator is needed to help humans withstand the pressure at even the average depth of the ocean—which is 380 times greater than at the surface, according to the U.S. National Oceanic and Atmospheric Administration.

Alvin, the first U.S. human-operated vessel dedicated to scientific research, made it possible for humans to dive for up to nine hours at 4,500 meters. The vessel was developed in 1964 by a research team led by geophysicist Allyn C. Vine at the Woods Hole Oceanographic Institution (WHOI), in Falmouth, Mass.

Thanks to *Alvin*, scientists were able to study the effects of pressure on seafloor microbes, and they discovered hydrothermal vents that help regulate ocean chemistry and support ecosystems.

In addition to scientific research, the submersible conducted several expeditions for the U.S. Navy. During its first major deployment in 1966, the vessel was sent to search for a hydrogen bomb that accidently was dropped in the Mediterranean Sea after a U.S. Air Force bomber and a tanker collided over Spain. It took *Alvin* two months to find it.

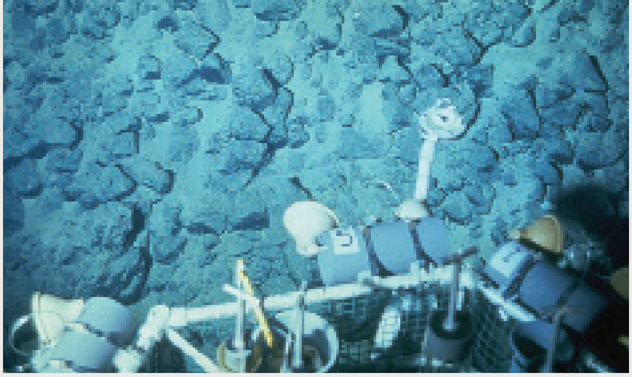
The submersible, which is still used today, has been commemorated with an IEEE Milestone. The IEEE Providence (R.I.) Section sponsored the nomination. Due to the COVID-19 pandemic, the dedication ceremony is still being planned.

Administered by the IEEE History Center and supported by donors, the Milestone program recognizes outstanding technical developments around the world.

The necessary push

Although *Alvin* wasn't the first human-operated underwater vehicle, its predecessors were larger and difficult to maneuver. In a 2015 interview with the WGBH Forum Network, Dudley Foster, an engineer who worked on *Alvin,* described the previous submersibles as "blimps."

During a 1956 symposium about deep-sea exploration held in



Top: Scientists use *Alvin*'s robotic arms to collect samples of sediment and marine life. Bottom: The vessel in Eel Pond in Woods Hole, Mass.

Washington, D.C., the U.S. Office of Naval Research made a presentation about one of the submersibles: *Trieste*. After the conference, the research office sent a delegation, including Vine, to Italy to see the 18-meter-long, 45-tonne vehicle.

The U.S. Navy purchased *Trieste* in 1958 to conduct research. When in 1960 it made an expedition to Challenger Deep, the nethermost point of the Mariana Trench, it was the first time a manned or unmanned vessel reached the deepest known point of Earth's oceans. But *Trieste* proved "too large and cumbersome for routine operations throughout the oceans," according to a 2014 *Eos* article.

Vine and his research team, the WHOI Deep Submergence Group, in collaboration with the research office, requested bids to build a smaller and more maneuverable submersible. General Mills, in Minneapolis, secured the contract with a bid of US $498,500, according to the *Eos* article.

Revolutionary engineering

Alvin, which was named after Vine, was designed by General Mills engineer Harold "Bud" Froelich. The vessel's frame was built using syntactic foam, which was buoyant and strong enough to withstand extreme pressure. *Alvin* weighed 15 tonnes and was about 7 meters long, according to WHOI. The vessel was completed in 1964.

Propulsion equipment was housed in the back of the vehicle along with three lead-acid batteries and five buoyancy spheres, which controlled its vertical movement. Electrical and fiber-optic connectors and cables were encapsulated in oil-filled hoses and boxes, making them waterproof. To help *Alvin* withstand the high pressure, the back was open so that seawater could flow around the equipment.

The researchers and pilot sat in a sphere at the front of the submersible. The steel sphere, which was about 2 meters in diameter and had three plexiglass windows, housed life-support systems. In an emergency, the sphere could detach and float to the surface. *Alvin* also had landing skids so that it could sit on the ocean floor.

Equipment in the sphere controlled the submersible as well as two robotic arms and cameras that were mounted on the front. The arms could be fitted with probes and tools to take samples of sediment and marine life. A specially designed insulated box ensured that collected samples weren't ruined by changes in water temperature or pressure, according to Foster. *Alvin's* still cameras used thallium iodide lights to illuminate the seafloor—which, he says, emitted a green light rather than white light. The former travels through water better and allowed for brighter photos.

Amazing achievements

Alvin's first major scientific discovery happened by accident in 1968, when the submersible sank about 1,500 meters to the bottom of the ocean. A cable snapped while the vehicle was being lifted out of the surface ship that had carried it 217 km off the Massachusetts coast to look for whales. The crew escaped unharmed, but the items they brought for lunch sank with the ship.

When *Alvin* was recovered a year later, the food—which included soup, bologna sandwiches, and apple slices—was "essentially intact," according to the Milestone's entry on the Engineering and Technology History Wiki. Researchers investigated why the items didn't decay as they would have on the surface. They discovered that the pressure suppressed the growth of the surface bacteria that was in the food.

Another important discovery—hydrothermal vents—was made on a research trip led by oceanographer Jack Corliss in the Galapagos Rift, located in the South Pacific.

"Hydrothermal vents spew poisonous superheated gas and metal-laden water, and yet scientists saw creatures such as giant tube worms, clams, and mussels thriving in the environment," says a 2020 *Medium* article about *Alvin*.

Corliss saw that the ecosystem was isolated from sunlight and soon after, according to the 2020 article, theorized that life might have first emerged around such vents.

"Corliss believed that hydrothermal vents contained all the conditions necessary for the origin of life on Earth," the *Medium* article states.

During the past six decades, *Alvin's* equipment has been upgraded many times. It now includes an acoustic navigation system, high-resolution digital cameras, a video system, and syntactic foam modules. ■

WOODS HOLE OCEANOGRAPHIC INSTITUTION

IEEE PRODUCTS

Internet for All Corners

BY IEEE STANDARDS ASSOCIATION

ALMOST HALF the world's population has no Internet access, according to the World Economic Forum. And where access is available, it can be too expensive. The IEEE Standards Association Connectivity and Telecom Practice is working on the issue, researching communities' needs and collaborating with other organizations.

The group has released five videotaped interviews with industry professionals, researchers, and policymakers working on challenges in Africa, India, Indonesia, and Mexico.

Designing a User-Centered Interface for Rural Communities. The chair of the IEEE Standards Association Connectivity and Telecom Practice, IEEE Associate Member Anmol Anubhai, shares her real-world experience and discusses how the program can help raise computer literacy.

Accelerating Africa's Digital Transformation Through ICTs. Lacina Koné, director general and chief executive of Smart Africa, covers current efforts by African leaders to transform the continent's digital future and accelerate socioeconomic development through information and communications technologies (ICT).

Connecting Rural India Through Technology Standards. Not enough people living in rural areas are using the reliable Internet infrastructure the government has provided, because accessing it is too expensive, says Sandeep Agrawal, team leader of the Centre for Development of Telematics in Bangalore. Agrawal, an IEEE senior member, discusses other challenges as well. He also talks about two standards programs he chairs: the IEEE P2872 Working Group for Interoperable and Secure Public Wi-Fi Infrastructure and Architecture and the Rural Communication Industry Connections Program.

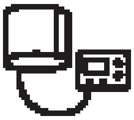
Protecting Data Privacy in the Use of ICTs in Indonesia. Benjamin Hsueh-Yung Koo, director of international relations for the iCenter at Tsinghua University, in Beijing, examines policy and educational challenges and how technicalstandards can support sustainable and trustworthy data governance.

Bridging Digital Divide in Mexico Through Collaborative Regulation. Paola Cicero, chief of staff at Mexico's Federal Institute of Telecommunications, discusses how to provide universal connectivity by leveraging local IEEE resources and developing collaborative regulation such as sharing guiding principles and best practices and defining mechanisms for cooperation. ■

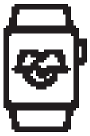
IEEE STANDARDS

6 Medical Devices With IEEE Standards Inside

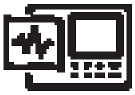
YOU MIGHT NOT realize it, but IEEE standards can be found in a variety of well-known medical devices used both at home and in hospitals. Standards help make devices more reliable and ensure their interoperability. From electrocardiographs to glucose meters, you or someone you know has probably used at least one of these.



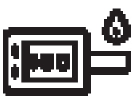
Blood pressure monitor
IEEE 11073-10407



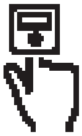
Cardiovascular fitness and activity monitor
IEEE 11073-10441



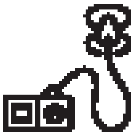
Electrocardiograph
IEEE 11073-10406



Glucose meter
IEEE 11073-10417



Pulse oximeter
IEEE 11073-10404



Sleep apnea breathing therapy equipment
IEEE 11073-10424

SOURCE: IEEE STANDARDS ASSOCIATION

ISTOCK PHOTO

Psyonic's Ability Hand offers 32 different grips. It weighs around the same as an average adult hand.

STARTUP

Haptic Hand Gives Amputees Sense of Touch

Psyonic's prosthesis vibrates to provide feedback

BY JOANNA GOODRICH

ON A VISIT to Pakistan with his parents, 7-year-old Aadeel Akhtar met a girl his age who was missing her right leg. That was the first time he had met a person with a limb difference. The girl's family could not afford the cost of getting her a prosthetic leg, so she used a tree branch as a crutch to help her walk. From that encounter, Akhtar decided that one day he would develop affordable artificial limbs.

Twenty-one years later, in 2015, the IEEE member founded Psyonic, which designs and builds advanced, affordable artificial limbs. Akhtar is the CEO. The startup, headquartered in Champaign, Ill., released its first product—the Ability Hand—in September 2021. It is the fastest bionic hand on the market and the only one with touch feedback.

The prosthesis uses pressure sensors to mimic the sensation of touch through vibrations. It functions almost like a regular hand. All five fingers on the lightweight prosthesis flex and extend. It offers 32 different grips.

"The most important thing for us is to give people a functioning, robust prosthesis that allows them to do things they never thought they would be able to do again," Akhtar says.

Making prosthetic limbs accessible

Akhtar originally wanted to work with people with amputations as a physician. He earned a bachelor's degree in biology in 2007 from Loyola University in Chicago. But while pursuing his degree, he took a computer science course and fell in love with the subject.

"I loved everything about engineering, programming, and building things," he says. "I wanted to figure out a way to combine my interests in both engineering and medicine."

He went on to earn a master's degree in computer science in 2008, also from Loyola. Two years later he was accepted into the Medical Scholars Program at the University of Illinois at Urbana-Champaign. The program allows students to earn both an M.D. and a Ph.D. in tandem. Akhtar earned an additional master's degree in electrical and computer engineering and a doctorate in neuroscience in 2016.

PSYONIC

His research for his doctorate focused on developing what eventually became the Ability Hand.

In 2014 he and another graduate student, Mary Nguyen, partnered with the Range of Motion Project, a nonprofit that provides prosthetic devices to people around the world who can't afford them. Akhtar and Nguyen flew to Quito, Ecuador, to test their product on Juan Suquillo, who lost his left hand in 1979.

Using the prototype, Suquillo was able to pinch together his thumb and index finger for the first time in 35 years. He reported that he felt as though a part of him had come back thanks to the prosthesis. That feedback inspired Akhtar to found Psyonic when he returned from his trip.

To get some advice about how to run the company and possibly win some money, he entered the Cozad New Venture Challenge at the University of Illinois. The competition provides mentoring to teams, as well as workshops on topics such as pitching skills and customer development.

Psyonic placed first and received a US $10,000 prize. Since then, Psyonic has received funding from the University of Illinois Technology Entrepreneur Center, the iVenture Accelerator, and the U.S. National Science Foundation.

The startup has 23 employees including engineers, public health experts, social workers, and doctors.

Developing the Ability Hand

Psyonic's artificial hand weighs 500 grams, around the weight of an average adult hand. Most prosthetic hands weigh about 20 percent more, Akhtar says. The Ability Hand contains six motors housed in a carbon fiber casing. It has silicone fingers, a battery pack, and muscle sensors that are placed over the patient's residual limb.

If the patient has an amputation below the elbow, for example, two muscle sensors would be placed over the intact forearm muscle. The patient could then use those sensors to control the hand's movement and grip.

The Ability Hand is connected by Bluetooth to a smartphone app, which provides users another way to configure and control the hand's movements. The hand's software is automatically updated through the app. Its battery recharges in an hour, the company says.

While talking with patients who used prosthetic hands, Akhtar says, he learned they had issues such as a lack of sensation and frequent breakage.

To give patients a sense of touch, the Ability Hand contains pressure sensors on the index finger, pinky, and thumb. When patients touch an item, they will feel vibrations on their skin that mimic the sensation of touch. The prosthesis uses those vibrations to alert users when they touch an object as well as indicate how hard they have grabbed it and when they have let go.

The reason most prosthetic limbs break, Akhtar says, is because they are made of rigid materials such as plastic, wood, or metal, which can't bend when they hit a hard surface. Psyonic uses rubber and silicone to make the fingers, which are flexible and can withstand a great deal of force, he says.

"Everything we do has the patient in mind," Akhtar says. "We want to improve the quality of life for people with limb differences as much as possible. Seeing the effect the Ability Hand has already had on people in such a short time span motivates us to keep going."

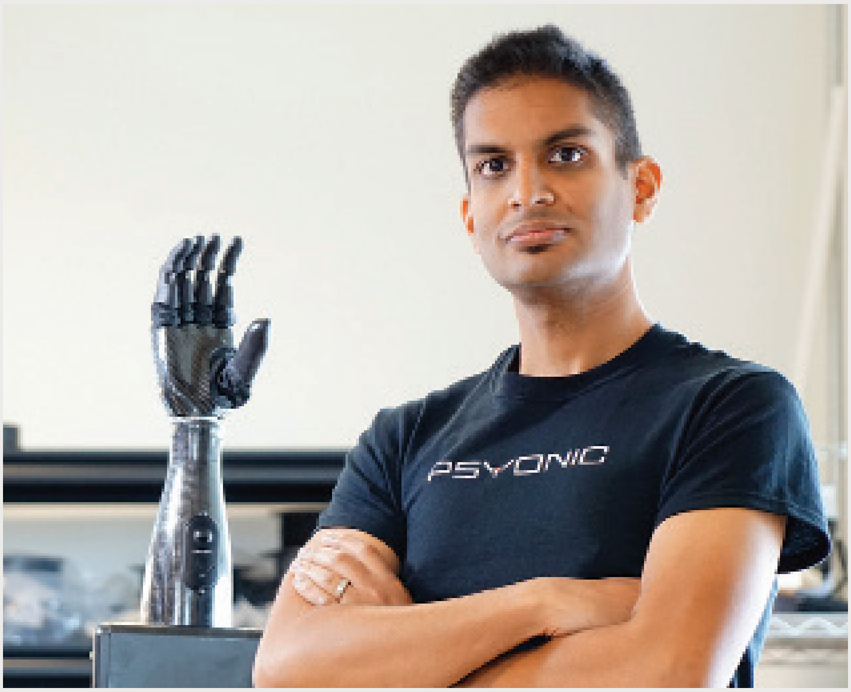
Psyonic and its partners are researching how to improve the artificial hand. Akhtar says some of the partners, including the Ryan AbilityLab in Chicago and the University of Pittsburgh, are developing brain and spinal-cord implants that could help patients control the prosthesis.

Positive feedback

Akhtar joined IEEE in 2010 when he was a doctoral student.

IEEE provides a great "ecosystem," he says, on prosthetic limbs and robotics, and "it's amazing to be part of that community."

He adds that having access to IEEE's community of scholars and professionals, some of whom are pioneers in the field, has helped the company gain important feedback on how it can improve the hand, as well as help in the development of legs in the future. ■



PSYONIC

The startup's founder, Aadeel Akhtar, was inspired to develop artificial limbs during a trip to Pakistan when he was 7 years old.

IEEE ELECTION

Countdown to the IEEE Annual Election

ON 1 MAY the IEEE Board of Directors is scheduled to announce the candidates to be placed on this year's ballot for the annual election of officers—which begins on 15 August.

The ballot includes IEEE president-elect candidates and other officer positions up for election, as well as a proposed amendment to the IEEE Constitution.

The Board of Directors has nominated Life Fellow Thomas Coughlin and Senior Members Kathleen Kramer and Maike Luiken as candidates for 2023 IEEE president-elect. IEEE Life Fellow Kazuhiro Kosuge is seeking nomination by petition for the position. Visit the IEEE elections page (ieee.org/elections) to learn about the candidates and petitioner, as well as the petition process and petition(s) available for members to sign.

The ballot includes nominees for delegate-elect/director-elect openings submitted by division and region nominating committees, IEEE Technical Activities vice president-elect, IEEE-USA president-elect, and IEEE Standards Association board of governors members-at-large.

IEEE members who want to run for an office but who have not been nominated need to submit their petition intention to the IEEE Board of Directors. Petitions should be sent to the IEEE Corporate Governance staff: elections@ieee.org.

Those elected take office on 1 January 2023.

The Board of Directors voted at its November meeting to propose an amendment to the IEEE Constitution to be part of the 2022 IEEE annual election. The proposal, if adopted, would change the member-initiated constitutional amendment petition requirement by establishing greater member support for member-initiated petitions before ballot placement and enhancing membership's global voice in proposing constitutional changes.

Members are encouraged to participate in the online forum discussion (ieee-collabratec.ieee.org/app/community/1355/Draft-Constitutional-Amendment-Nov-2021/activities).

To ensure voting eligibility, members are encouraged to review and update their contact information (ieee.org/go/my_account) and communication preferences (ieee.org/election-preferences) by 30 June.

Given ever-changing global conditions, members might wish to vote electronically instead of by mail.

For more information about the offices up for election, the process of getting on the ballot, and deadlines, visit the IEEE elections page (ieee.org/election) or write to elections@ieee.org.

2021 Election Results

Here is the IEEE Tellers Committee tally of votes counted in the 2021 annual election and approved in November by the IEEE Board of Directors.

IEEE president-elect, 2022
Saifur Rahman: 13,296
S.K. Ramesh: 13,013
Thomas M. Coughlin: 11,802
Francis B. Grosz: 6,308

IEEE division delegate-elect/director-elect, 2022
Division II
Kevin L. Peterson: 2,347
Homer Alan Mantooth: 2,071

Division IV
Alistair P. Duffy: 1,583
Peter N. Clout: 1,228
Bruce P. Strauss: 1,218

Division VI
Kamal Al-Haddad: 1,649
Stefan G. Mozar: 1,637

Division VIII
Leila De Floriani: 4,097
Sorel Reisman: 1,209

Division X
Stephanie M. White: 2,959
Jacek M. Zurada: 2,248

IEEE region delegate-elect/director-elect, 2022—2023
Region 1
Bala S. Prasanna: 1,761
Ali Abedi: 1,601

Region 3
Eric Grigorian: 1,660
John Patrick "Pat" Donohoe: 1,472

Region 5
Anthony M. "Matt" Francis: 1,660
Hunter Boudreaux: 920

Region 7
Thamir "Tom" F. Murad: 903
Mohammed Khalid: 586

Region 9
Jenifer P. Castillo Rodriguez: 1,045
Jorge E. Monzón: 577

IEEE Standards Association president-elect, 2022
Yu Yuan: 653
Mark Epstein: 612
Robby Robson: 423
Yatin Trivedi: 341

IEEE Standards Association board of governors member-at-large, 2022—2023
Glenn W. Parsons: 1,144
Kishik Park: 675

IEEE Standards Association board of governors member-at-large, 2022—2023
Mehmet Ulema: 984
Sha Wei: 907

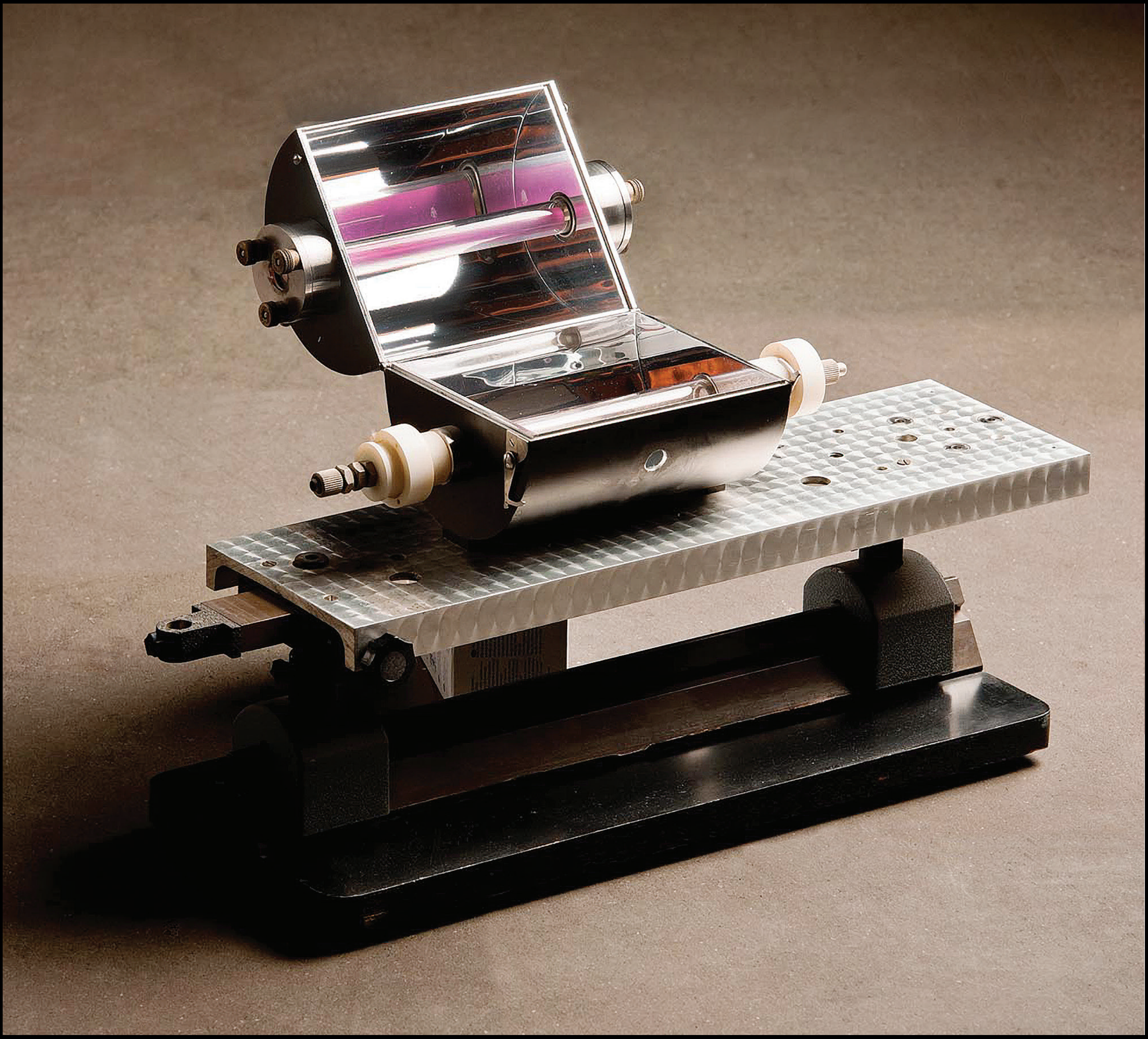
IEEE Technical Activities vice president—elect, 2022
John P. Verboncoeur: 14,456
Maciej J. Ogorzalek: 11,939

IEEE-USA president-elect, 2022
Eduardo "Ed" F. Palacio: 9,651
Keith A. Moore: 9,625

IEEE Women in Engineering Committee chair-elect, 2022
Celia Shahnaz: 1,110
Cinzia Da Vià: 449
Simay Akar: 441

BY ALLISON MARSH

Past Forward



PAUL WILKINSON/ROYAL INSTITUTION

The Nobelist's First Laser

When George Porter arrived at the University of Cambridge in 1945 as a Ph.D. student, he found the equipment remarkably primitive. Students had to build their own oscilloscopes! To conduct his research—detecting the short-lived molecules known as free radicals—Porter pieced together a setup that included a surplus army searchlight powered by a surplus diesel engine. After seeing flash lamps at a Siemens factory, he decided to modify his approach, replacing the continuous light source with short, intense pulses of light. With his flash photolysis technique, Porter was able to capture reactions lasting mere milliseconds. To study even faster reactions, though, he needed a faster light source, for which he'd have to wait. The ruby laser, invented in 1960, was the ideal solution. Porter used this one to record nanosecond-scale reactions. Flash photolysis is still used to study semiconductors, nanoparticles, and photosynthesis, among other things. For their work on high-speed, light-driven chemical reactions, Porter; his Ph.D. adviser, Ronald G.W. Norrish; and Manfred Eigen shared the 1967 Nobel Prize in Chemistry. ■

FOR MORE ON GEORGE PORTER'S CONTRIBUTIONS, SEE spectrum.ieee.org/pastforward-mar2022

Semantic segmentation for wildlife conservation.