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FOR THE TECHNOLOGY INSIDER

SEPTEMBER 2022

IEEE Spectrum

Engineering the James Webb Space Telescope

IEEE

Contents

TOP: DAPPER LABS; BOTTOM: TSMC

BY HARRY GOLDSTEIN

How We Celebrate Engineers

The Institute focuses on fascinating people and the technology they create

IEEE members recently featured in *The Institute* [clockwise from top left]: Arti Agrawal, Ramneek Kalra, Jack Dongarra, Sandra Johnson, and Michael Kagan.

The Institute has appeared, off and on, in these pages since debuting as a four-page insert in the December 1976 issue of *IEEE Spectrum*. At various times during the ensuing decades, *The Institute*—or, as we call it in *Spectrum*'s offices, "*TI*"—has been published as a stand-alone monthly and then a quarterly broadsheet. It even had its own website for a few years, before being integrated into *Spectrum*'s site in 2019 and appearing in these pages as a section on a quarterly basis.

While *Spectrum* dives deep into emerging technologies and delivers expert voices from the bleeding edge, since its start *The Institute* has focused on IEEE members, featuring their stories, celebrating their accomplishments, and telling them about IEEE products, services, elections, and volunteer opportunities. *The Institute* also brings members all the news relevant to the functioning of the association, such as the reconfiguration of its geographic regions to ensure there is equitable representation across its global membership.

The Institute staff—Editor in Chief Kathy Pretz and Assistant Editor Joanna Goodrich—say they are most excited about showcasing the diversity of IEEE's membership and highlighting those who have made IEEE their professional home. Pretz says there's a misconception that most of IEEE's members work in academia. That's why *The Institute* has put more emphasis on profiling the careers of those working in industry, such as Taiwan Semiconductor Manufacturing Co.'s senior vice president of R&D, Yuh-Jier Mii.

"I'm always amazed how accessible top leaders at high-tech companies are when I tell them I would like to interview them for an article in IEEE's member publication," Pretz remarked recently. "And all of them are so humble about their accomplishments. TSMC's Yuh-Jier Mii was no different."

"It's very rewarding to be able to interview members who have developed technology that I use every day."

Pretz and Goodrich also write about the careers of young professionals who are the future of the organization. In this month's issue they spotlight Eddie Custovic, the recipient of the IEEE Theodore W. Hissey Outstanding Young Professionals Award.

In addition to putting a spotlight on the accomplishments of individual engineers, *The Institute* also covers the history of technology. "It's very rewarding to be able to interview members who have developed technology that I use every day, as well as members who are developing the next breakthrough tech that will impact society," Goodrich says. "For example, Steven Sasson invented the first digital camera, which we use every day in some shape or form. Eddie Custovic, on the other hand, is working to develop an AI platform that will help solve food shortages that have been predicted for 2050."

Indeed, IEEE members have for decades been turning their ideas into successful businesses. That's why *TI* features entrepreneurial members who have launched their own ventures, like IEEE Fellow Alex Bronstein, of Embryonics. And, of course, *TI* celebrates major anniversaries and milestones, like the 25th anniversary of IEEE Women in Engineering.

In future issues, readers can look forward to a profile of computer pioneer IEEE Fellow Erol Gelenbe, whose invention of the packet-voice telephone switch made Zoom possible. In December, look for a piece on IEEE executive director Stephen Welby, who is leaving the organization at the end of the year. Kathy, Joanna, and I invite you to celebrate these engineers and their extraordinary accomplishments with us in the coming months. ■

PORTRAIT BY SERGIO ALBIAC

Photo-Illustration by Gluekit

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NATASHA BAJEMA

By day, Bajema works at the National Defense University, in Washington, D.C. By night, she writes mystery novels, notably the Lara Kingsley series of political thrillers. She says her interest in submarine warfare comes from a "growing fascination with how artificial intelligence…may someday lead to full transparency in all things, including nuclear weapons." See "Will AI Steal Submarines' Stealth?" on page 36.

JEFF HECHT

Hecht is a veteran technology reporter and a life senior member of IEEE. He says he's been fascinated by the James Webb Space Telescope for decades and "jumped at the chance to write about it." See the results on page 22.

TOBIAS MOSER

Moser heads the Institute for Auditory Neuroscience at the University Medical Center Göttingen, in Germany. He's developing a new type of cochlear implant using a novel form of gene therapy and optoelectronics [p. 30]. Moser is motivated by his interactions with his patients. "I know full well what today's cochlear implant can do for them, and what it cannot," he says. "I want to offer them something better."

NED POTTER

An *IEEE Spectrum* contributor since 2019, Potter spent more than 25 years as a science and technology correspondent for ABC News and CBS News. For a series about the Hubble telescope, he once successfully landed a space shuttle simulator. Potter reports on the engineering of the James Webb Space Telescope on page 22.

MATTHEW S. SMITH

Smith is a freelance consumer-tech journalist. He investigates the rise and fall of the first nonfungible-token game, *CryptoKitties*, on page 42. He wasn't really shocked by its success. "Spending real money on a picture of a cat may seem strange, but I remember people spending thousands of dollars on eBay to buy virtual swords in early online games," he says.

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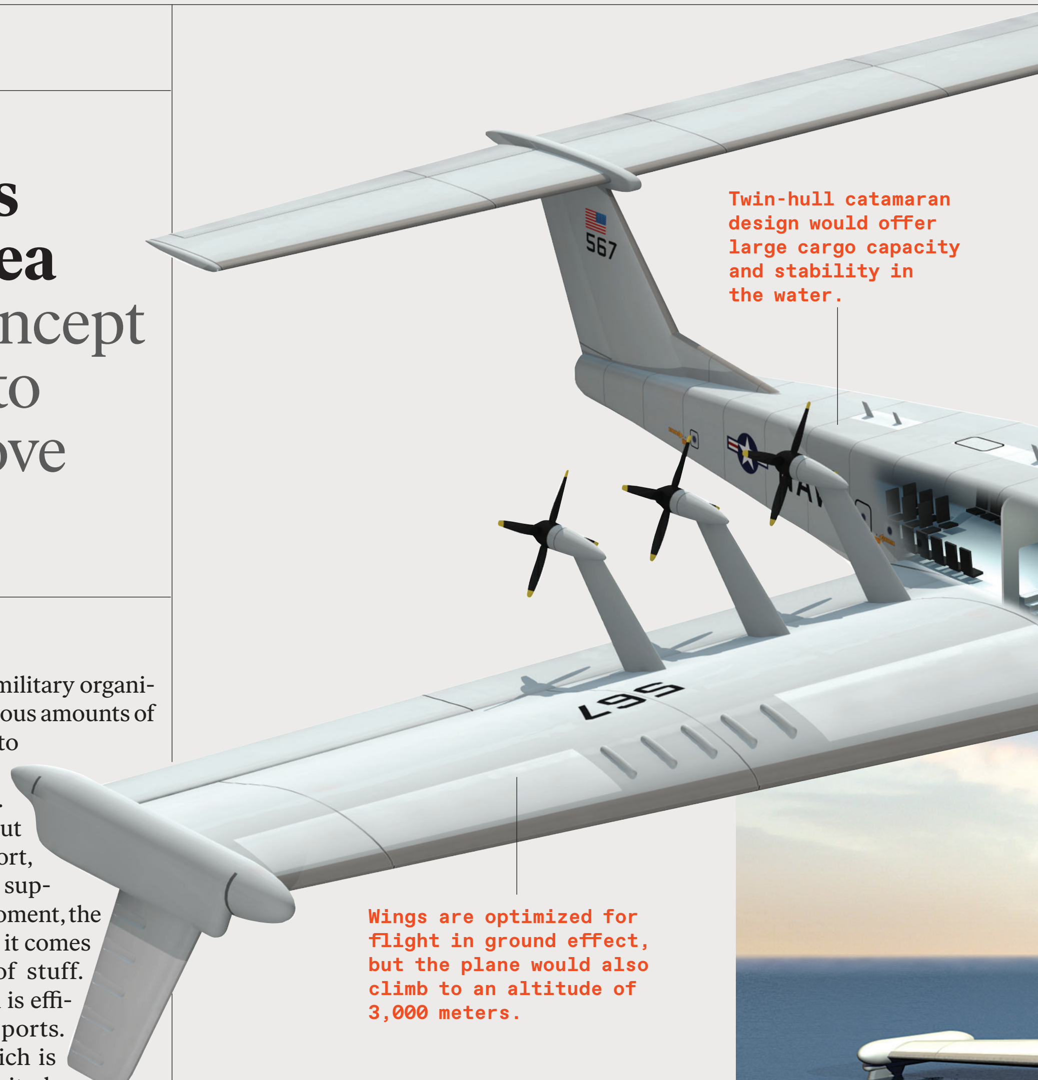
News

AEROSPACE

DARPA Reincarnates Soviet-Era Sea Monster › Concept sea skimmer to fly meters above the ocean

BY EVAN ACKERMAN



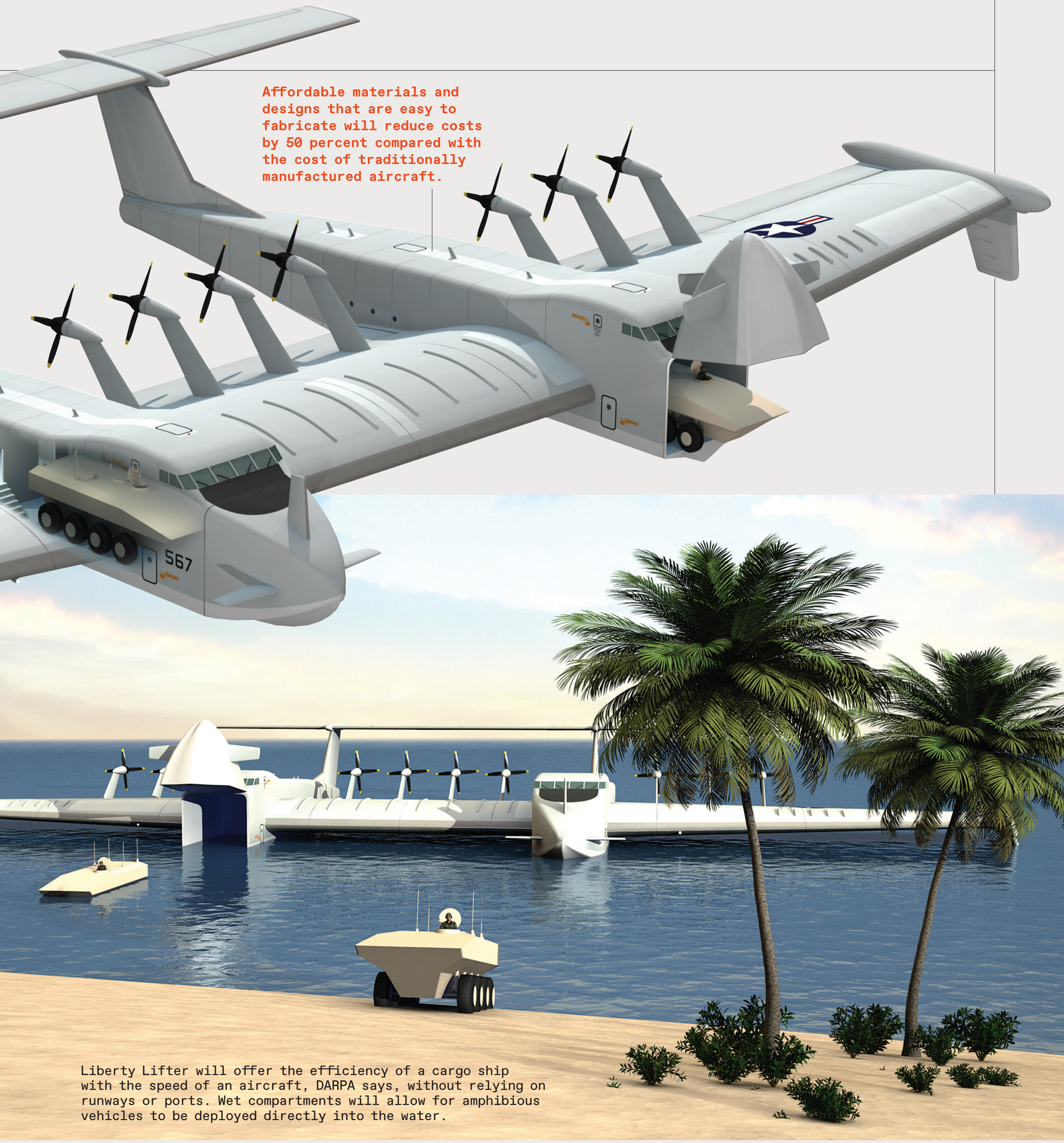
The primary job of any military organization is moving enormous amounts of stuff from one place to another as quickly and efficiently as possible. Sometimes that stuff is weaponry, but most of the time it's logistical support, like food, fuel, spare parts, medical supplies, personnel, and so on. At the moment, the U.S. military has two options when it comes to transporting large amounts of stuff. Option one is ships (sealift), which is efficient but also slow and requires ports. Option two is planes (airlift), which is faster by a couple of orders of magnitude but also expensive and requires runways.

To solve this, the Defense Advanced Research Projects Agency (DARPA) wants to combine traditional sealift and airlift with Liberty Lifter, a new program to develop an "affordable, innovative, and disruptive" seaplane that skims across the ocean to efficiently transport large payloads faster than a ship ever could.

The key concept behind Liberty Lifter is what's called "ground effect." As the wing of a moving aircraft deflects air downward, proximity to the ground generates a cushioning effect due to the compression of air between the bottom of the wing and the ground, boosting lift and lowering drag to yield a substantial improvement in efficiency. The name is somewhat deceptive in that ground effect works over both water and land. However, gliding just above the land surface can work for only so long before you run into something, which is why oceans are the ideal place for these air- and seacraft.

During the late 1980s, the Soviets (and later the Russians) leveraged ground effect in the design of a small number of unique air- and seacraft, including the Bartini Beriev VVA-14, which could also fly like a traditional airplane, and the *Lun*-class ekranoplan, which was limited to skimming above the water in ground-effect mode. The latter operated until the late 1990s.

The *Lun* (only one was ever built) had a wingspan of 44 meters and was powered by eight turbofan



Liberty Lifter will offer the efficiency of a cargo ship with the speed of an aircraft, DARPA says, without relying on runways or ports. Wet compartments will allow for amphibious vehicles to be deployed directly into the water.

Illustrations by John MacNeill

engines, lined up together in two clusters extending out from either side of the front of the fuselage in order to keep the engines from ingesting spray. *Lun* flew as low as 1.5 meters above the water at speeds of up to 550 kilometers per hour, and could transport almost 137 tonnes of cargo a distance of 2,000 km. *Lun* was based on an earlier, even larger prototype (the largest aircraft in the world at the time) called *Korabl Maket* ("ship maquette," in Russian) or KM. The CIA spotted it in spy-satellite images in 1967 and nicknamed it the "Caspian Sea Monster." It wasn't until the 1980s that the West understood what it was and how it worked.

In the mid 1990s, DARPA itself took a serious look at ekranoplan-inspired designs, including a stupendously large ground-effect vehicle called the Aerocon Dash 1.6 wingship. The concept was for a 4.5-million-kilogram vehicle, 172 meters long with a 104-meter wingspan, powered by up to 20 jet engines. With a range of 18,500 km at over 740 km/h, the wingship could have carried over 2,000 passengers, plus 1.4 million kg of cargo. By 1994, though, DARPA had decided that the potential billion-dollar project to build such a wingship was both too expensive and too risky, and canceled the whole thing.

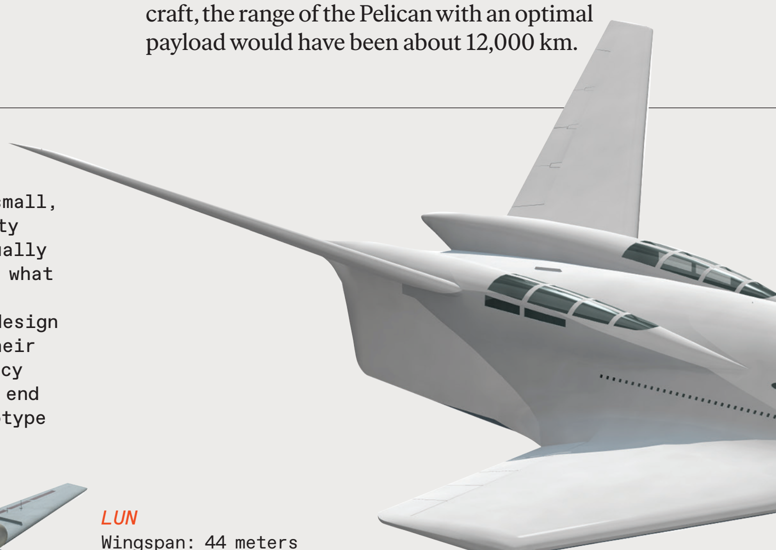
DARPA's biggest challenge: a low-cost design and construction philosophy inspired by the mass-produced Liberty ships of World War II.

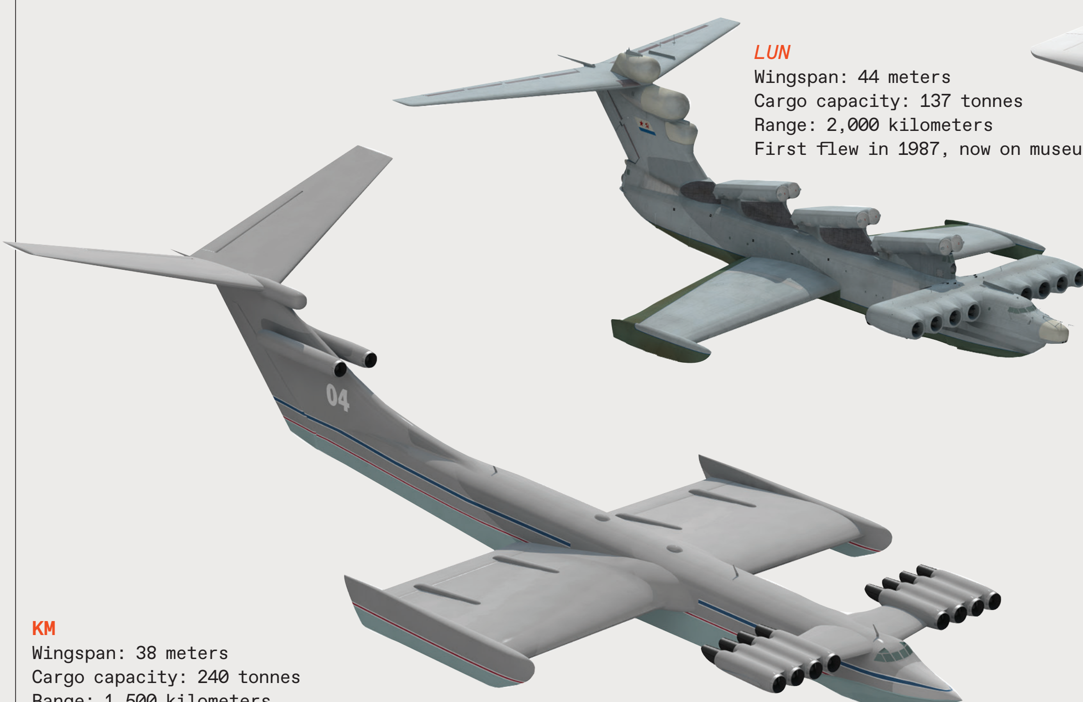
Less than 10 years later, Boeing's Phantom Works started exploring an enormous ground-effect aircraft, the Pelican Ultra Large Transport Aircraft. The Pelican would have been even larger than the Aerocon wingship, with a wingspan of 152 meters, and would handle a payload of 1.27 million kg—that's about 178 shipping containers' worth of stuff. The Pelican would have taken advantage of ground effect to boost efficiency in transit above water, but would otherwise use runways and be able to reach flight altitudes of 6,100 meters or more. Operating as a traditional aircraft, the range of the Pelican with an optimal payload would have been about 12,000 km.

FLIGHTS OF FANCY

Wingships, both real and conceptual, range in size from small, single-person vehicles to gigantic cargo carriers. Liberty Lifter will be somewhere in between what the Soviets actually built and flew, like the VVA-14, the KM, and the *Lun*, and what DARPA thought might be possible, like the Aerocon Dash.

While DARPA sees advantages in a twin-hull catamaran design for Liberty Lifter, it's up to manufacturers to submit their best ideas for meeting the goals of the program. The agency expects announcements about industry partnerships by the end of this year, with the first flight of a full-scale prototype expected as early as 2027.





LUN
Wingspan: 44 meters
Cargo capacity: 137 tonnes
Range: 2,000 kilometers
First flew in 1987, now on museum display

KM
Wingspan: 38 meters
Cargo capacity: 240 tonnes
Range: 1,500 kilometers
First flew in 1966, sunk in 1980

Illustration by John MacNeill

In ground effect, however, the plane's range would have increased to 18,500 km, illustrating the substantial advantage of designs like these. But Boeing dropped the project in 2005 to focus on lower-cost, less risky options.

The Liberty Lifter program is managed by Dr. Alexander M. G. Walan, a retired U.S. Air Force officer who most recently led advanced tech development projects at the Air Force Research Laboratory. "I was at DARPA looking for new ideas, and I inherited an old study on these wing-in-ground-effect vehicles," Walan tells *IEEE Spectrum*. "I was immediately intrigued, because I love the idea of taking these concepts that never quite made it and figuring out whether they were just ahead of their time. Maybe now the concept can work."

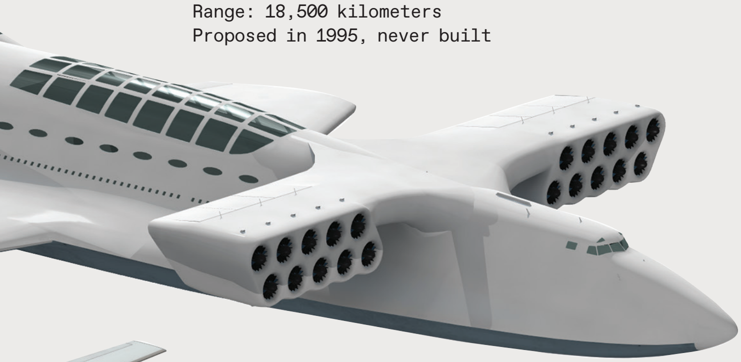
> **"It's not very often that you get a technology that changes how you operate."**
>
> —DR. ALEXANDER M.G. WALAN, AIR FORCE RESEARCH LABORATORY (RET.)

From the sound of DARPA's announcement, the agency is looking for something a bit more like the Pelican than the *Lun*, in operational concept if not in scale. One of the problems with the Soviet ekranoplans, according to Walan, is that because they were limited to flying in ground effect only, they were stuck operating in the sea in which they were deployed. They also flew only on calm days, since waves made them unstable. "We want to fly across the Pacific," Walan says, "and we want to do that over waves of up to 4 meters high—meaning that we could cross the ocean 90 percent of the time." The other 10 percent of the time, when the weather is bad enough that flying in ground effect isn't possible, Liberty Lifter can simply gain altitude. It will lose some efficiency by doing so, but it'll be able to avoid having to go around landmasses, and even deliver cargo inland using parachutes. "We take advantage of ground effect, but we're not reliant on it," Walan explains. Although touching down on land won't be an option, Walan sees that as an advantage rather than a disadvantage, since for Liberty Lifter, 70 percent of Earth's surface is effectively a runway.

Walan says that earlier wing-in-ground-effect concepts (including the Aerocon Dash wingship) were simply too big to be realistic in the context of the post-Cold War military drawdown of the 1990s. Meanwhile, Liberty Lifter will be, Walan says, "a big airplane, but not crazy big." DARPA is looking for an operational range of 7,500 km, with a maximum payload of at least 90,000 kg that includes the ability to launch and recover amphibious vehicles. The most challenging thing DARPA is asking for could be that Liberty Lifter should incorporate a low-cost design and construction philosophy inspired by the mass-produced Liberty ships of World War II. Recent advances in distributed propulsion and aluminum printing suggest that these vehicles could be built at a much lower cost than traditional aircraft of similar size.

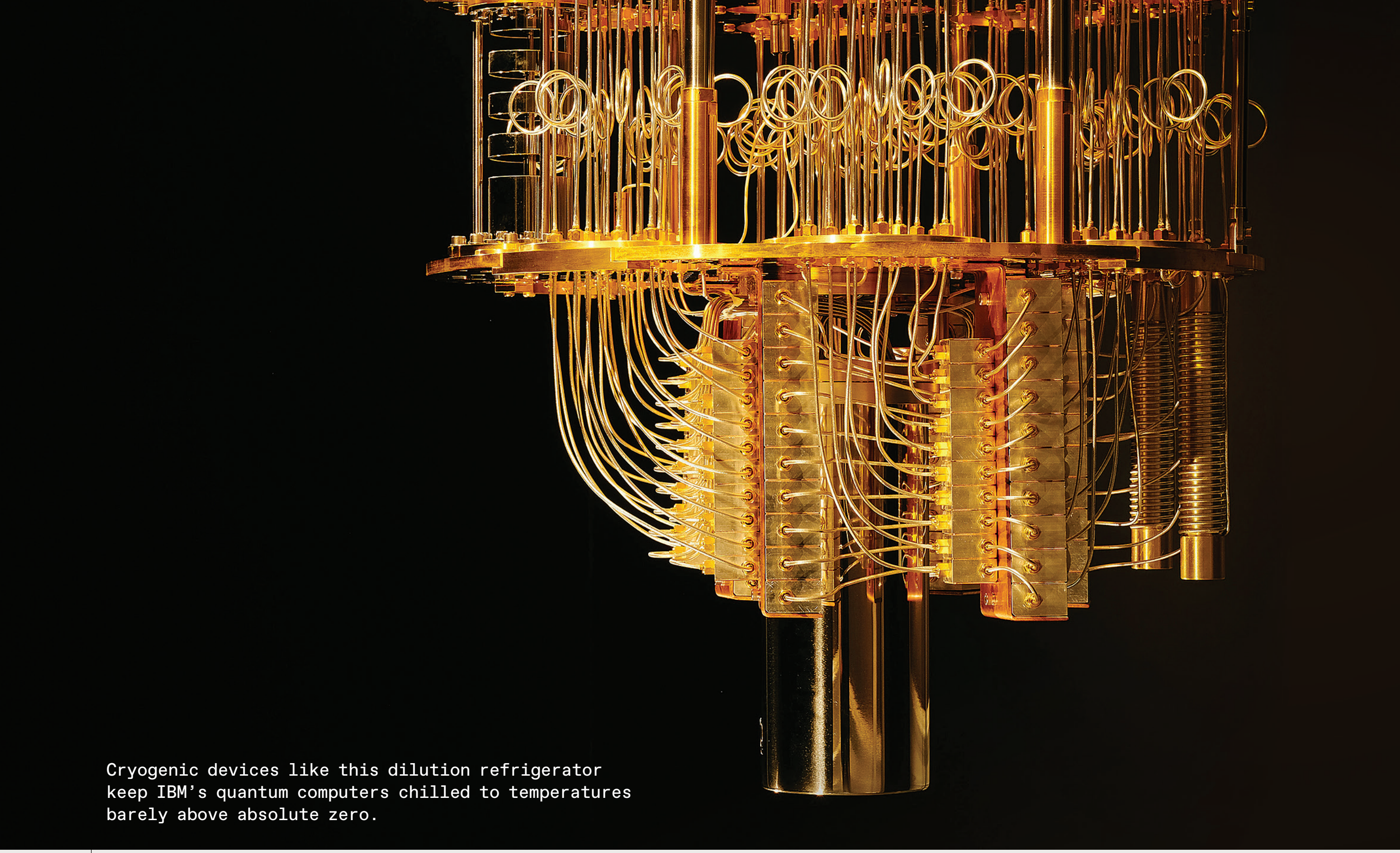
"I'm most excited about the operational disruption this might create—the ability to bridge the gap between airlift and sealift," Walan says. "It's not very often that you get a technology that changes how you operate." With US $15 million to be awarded to up to two Liberty Lifter concepts, DARPA is hoping that at least one of those concepts will pass a system-level critical design review in 2025. If everything goes well after that, the first flight of a full-scale prototype vehicle could happen as early as 2027. While the concept may seem futuristic, Walan is confident in the Liberty Lifter program. "It's hard to do something new and big and expensive, but we're committed to giving it a try." ■

AEROCON DASH 1.6
Wingspan: 104 meters
Cargo capacity: 1,560 tonnes
Range: 18,500 kilometers
Proposed in 1995, never built



LIBERTY LIFTER
Wingspan: 75 meters
Cargo capacity: 82 tonnes
Range: 7,500 kilometers
Proposed in 2022

VVA-14
Wingspan: 28 meters
Cargo capacity: 16 tonnes
Range: 2,500 kilometers
First flew in 1972, now on museum display



Cryogenic devices like this dilution refrigerator keep IBM's quantum computers chilled to temperatures barely above absolute zero.

IBM

COMPUTING

Quantum Computing for Classical Programmers ›

New guide helps beginners run quantum algorithms on IBM's quantum computers

BY CHARLES Q. CHOI

Quantum computers might one day rapidly find solutions to problems no regular computer could ever hope to solve, but there are vanishingly few quantum programmers when compared with the number of conventional programmers in the world. Now a group of quantum-computing experts at the Los Alamos National Laboratory, in New Mexico, have created a beginner's guide called "Quantum Algorithm Implementations for Beginners." The guide, which has been free to access on the Association for Computing Machinery's website since it first appeared in March, aims to walk would-be quantum programmers through the basics. The new guide explains the rudiments of quantum computing and quantum programming, including quantum algorithms.

The aim is to get neophyte quantum programmers prepared to implement quantum algorithms over the cloud on IBM's publicly available quantum computers.

Whereas classical computers switch transistors either on or off to symbolize data as ones or zeroes, quantum computers use quantum bits, or "qubits." Because of the "nonclassical" nature of quantum physics, qubits can exist in a state called superposition in which they are both 1 and 0 at the same time. This essentially lets each qubit perform two calculations at once. As more qubits are quantum-mechanically linked, or entangled within a quantum computer, its computational power grows exponentially.

Currently, quantum computers are noisy intermediate-scale quantum (NISQ) platforms, meaning their qubits number up to a few hundred at most and are error-ridden as well. Still, quantum processors are widely expected to improve in terms of both qubit count and quality. Ultimately, they will achieve a quantum advantage that enables them to find the answers to problems even the most powerful classical supercomputers could never solve.

Although the field of quantum programming started in the 1990s, it has to date drawn only a small community. "Programming quantum computers may seem like a great challenge, requiring years of training in quantum mechanics and related disciplines," says the guide's senior author, Andrey Lokhov, a research scientist at Los Alamos. "Additionally, the field is dominated by physics and algebraic notations that at times present unnecessary entry barriers for mainstream computer and mathematically trained scientists."

Now, with their new guide, Lokhov and his colleagues hope to help pave the way "for the upcoming quantum-computing revolution," he says. "We believe that our guide fills a missing space in the field of quantum computation, introducing nonexpert computer scientists, physicists, and engineers to quantum algorithms and their implementations on real-world quantum computers."

"Very much like how classical algorithms describe a sequence of instructions that need to be executed on a classical computer, a quantum algorithm represents a step-by-step procedure, where each of the steps needs to be performed on a quantum computer," Lokhov says. "However, the term 'quantum algorithm' is usually reserved for algorithms that contain inherently quantum operations, such as quantum superposition or quantum entanglement, which turn out to be computationally powerful."

To implement such quantum operations on quantum computers, quantum programs are represented as circuits describing a sequence of elementary operations, called gates, that are applied on a set of qubits. One major difference between quantum and classical programming lies in a central principle of quantum mechanics—when it comes to measuring a quantum program's results, the process is inherently probabilistic, or subject to random variation.

"Our guide aims to explain the basic principles of quantum programming, which are quite different from classical programming, with straightforward algebra that makes understanding the underlying fascinating quantum-mechanical principles optional," Lokhov says. "We have received positive feedback from many scientists—beginners in the field—who were able to quickly familiarize themselves with the basics of quantum programming using our guide."

The new guide provides the minimal knowledge needed to start implementing and running quantum algorithms right away. These include 20 standard quantum algorithms, including Shor's algorithm for factoring integers and Grover's algorithm for database searching.

"In addition, our review covers the most successful hybrid quantum-classical algorithms, such as the quantum approximate optimization algorithm, as well as classical tools that are useful for certifying the performance of quantum algorithms, such as quantum tomography," Lokhov says. "Hence, the guide surveys a combination of quantum, classical, and hybrid algorithms that are foundational for the field of quantum computing."

The guide then walks quantum programmers through implementing these algorithms over the cloud on IBM's publicly available quantum computers, such as its five-qubit IBMQX4. The guide discusses the results of the implementation and explains differences between the simulator and the actual hardware runs.

Lokhov notes that currently, in order to show that a new quantum algorithm works efficiently, one needs to give a mathematical proof. In contrast, in classical computing, many efficient algorithms were discovered heuristically—that is, by trial and error, or by loosely defined rules—with theoretical guarantees coming much later. The hope is that new quantum algorithms may get discovered in a similar fashion as more quantum programmers take up independent experimentation.

"We believe that our guide could be useful for introducing more scientists to quantum computing and for inviting them to experiment with the forthcoming quantum computers with larger numbers of qubits," Lokhov says.

You can find the code and implementations that accompany the guide at https://github.com/lanl/quantum_algorithms. ■

JOURNAL WATCH

A Blood-Sugar Breathalyzer for Diabetics

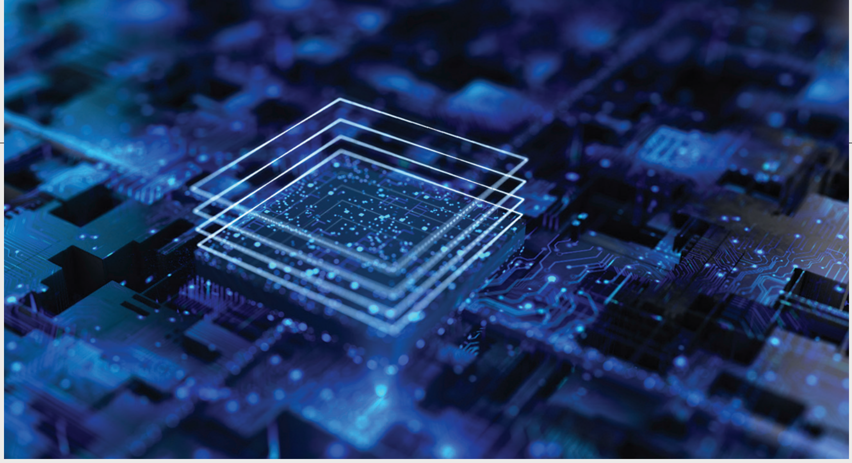
For years, Qiliang Li, a professor in the department of electrical and computer engineering at George Mason University, in Virginia, has been interested in developing e-nose technology for measuring glucose levels via a person's breath. Such a device would be a huge benefit to the more than 400 million people across the globe who live with diabetes. Although the amount of glucose exhaled from the lungs is minuscule, and therefore not easy to reliably correlate with the amount of glucose in the blood, there are other chemicals in the breath whose concentration can indicate human metabolic conditions, including diabetes.

Li and a multinational team of collaborators have designed an e-nose that reliably measures glucose levels based on a person's breath, offering people with diabetes a noninvasive alternative to the painful practice of pricking their fingers that is also wallet friendly. The device is described in a study published 7 June in *IEEE Sensors Journal*.

"The e-nose is designed to identify the 'smell' of acetone and other ketones [that are indirect but reliable] indicators of glucose level in the blood," says Li.

When the e-nose sniffs the exhaled breath, 12 chemical sensors send an electrical response to a microprocessor that translates the signals into digital information. "The e-nose will then analyze the digital information, [compare it with established values in] our database, and give a correct number representing the blood glucose level," explains Xiangdong Zhou, a professor of respiratory medicine at Nanjing Medical University, in China, who was also involved in the study.

The multinational team collected breath samples from 41 study participants with a range of glucose levels. They used the data to train the e-nose with a range of machine-learning algorithms until they found a combination of models that could detect glucose levels via a person's breath with 90.4 percent accuracy. **—Michelle Hampson**



SEMICONDUCTORS

RISC-V Guns for Raspberry Pi > Legacy chips could be unseated as open chip architecture gains adoption beyond the Internet of Things

BY LUCAS LAURSEN

Two hardware makers are planning to offer chips later this year that are based on the RISC-V reduced instruction set computing architecture standard. Those will join the US $180 Linux-capable StarFive VisionFive board based on the free-and-open architecture standard that went on sale last December. In late June, Pine64 said it was designing a single-board computer for the market now dominated by Raspberry Pi; Xcalibyte and DeepComputing said they would begin shipping RISC-V-based laptops at the end of the summer.

The 12-year-old RISC-V standard belongs to no one and everyone, giving it unique appeal compared with the proprietary setups that are the basis of Intel and Arm chips; those require licensing fees. That economic benefit notwithstanding, RISC-V's relative novelty and reduced feature set and support remain barriers to more widespread adoption. An open-source development effort last year to produce a Linux-capable mini-PC with RISC-V ended in failure. VisionFive was involved in that project, too. Like any new tech ecosystem, software support for the challenger is more limited than for the incumbent—in this case, Raspberry Pi, which has attracted a robust development community. So says independent software engineer Leon Anavi in a review of the VisionFive. Having said that, he encouraged viewers to join in and contribute to the growing RISC-V community.

RISC-V, which, as the acronym denotes, is the fifth generation of so-called reduced instruction set computers. This iteration is focused on simplicity and power efficiency. When the Internet of Things started to take off, RISC-V's moment seemed to have come; Huawei has used the standard in wearables since 2021. RISC-V could achieve a 25 percent market share in the IoT by 2025, Counterpoint Research estimated in late 2021.

"Consumer laptops are not the target of the RISC-V ecosystem," says research analyst William Li, the author of the Counterpoint report. "RISC-V is optimized for power consumption."

That has attracted AI-specific applications and cloud infrastructure ("RISC-V Dives Into AI," *IEEE Spectrum*, April 2022).

The openness of the standard has also attracted chipmakers facing limits on their use of Intel and Arm intellectual property: No government can place sanctions on open chip designs. That has been a concern for Chinese hardware makers since the trade war initiated by former U.S. president Donald Trump, and may help promote RISC-V sales in the event of restrictions on sales of Intel or Arm tech, wrote Deloitte analysts late last year. Alibaba has already taken some experimental steps in the direction of RISC-V, *IEEE Spectrum* wrote last year.

Russian hardware makers also began exploring RISC-V, even before the severe round of sanctions other countries placed on it after its 2022 escalation of its conflict with Ukraine.

"In the second half of this year, we will keep track of Chinese and Russian companies to see if they invest in RISC-V and are creating their own IP," says Li.

One Chinese research institute, the Institute of Software, Chinese Academy of Sciences (ISCAS), set out to build 2,000 RISC-powered laptops for development purposes, according to a July 2021 post by Wei Wu, director of the academy's Intelligence Software Research Center PLCT Lab. In the PLCT Lab's road map for 2022, Wu writes that the group will focus on enabling Linux and the most commonly used open software, including LibreOffice, for RISC-V laptops.

That is one of the ironies of RISC-V being an open standard: It may gain adoption as trade barriers fragment the global market for chips.

For now, however, the biggest market for RISC-V chips is in the global automotive industry, market research group Semico reported last year on behalf of the RISC-V International industry group. Semico predicted that RISC-V will continue to gain shares of the automotive market.

The future for chips may in fact be mixed, in a good way: Hardware makers can mix RISC-V, Arm, and Intel components in processor packages of their own making. Intel, for one, encourages that on the grounds that customers might end up paying them to build such chips.

And neither legacy-chip designer is standing still. Perhaps in response to RISC-V's customizability, Arm—which, although open, charges a license fee—has been offering IoT customers more customizable options. "They're going to try to defend their market share," Li predicts. ■

ISTOCKPHOTO

BIOMEDICAL

The Fatal Flaw of the Pulse Oximeter > Its design is delaying life-saving intervention for people with darker skin

BY REBECCA SOHN

If someone is seeking medical care, the color of their skin shouldn't matter. But, according to new research, pulse oximeters' performance and accuracy apparently hinge on it. Inaccurate blood-oxygen measurements made by pulse oximeters have had clear consequences for people of color during the COVID-19 pandemic.

Pulse oximeters work by passing light through part of the body, usually a finger. These devices infer a patient's blood-oxygen saturation (that is, the percentage of hemoglobin carrying oxygen) from the absorption of light by hemoglobin, the protein in blood that carries oxygen.

"That device ended up being essentially a gatekeeper for how we treat a lot of [COVID-19] patients," says Tianshi David Wu, an assistant professor of medicine at Baylor College of Medicine, in Houston, and one of the researchers who conducted the study.

Because low oxygen saturation, called hypoxemia, is a common symptom of COVID-19, low blood-oxygen levels qualify patients to receive certain medications. In the first study to examine this issue among COVID-19 patients, published in *JAMA Internal Medicine* in May, researchers found that the inaccurate measurements resulted in a "systematic failure," delaying care for many Black and Hispanic patients. In some cases, it prevented them from receiving proper medications altogether.

"If you have melanin, which is the pigment that's responsible for skin color,... that could potentially affect the transmittance of the light going through the skin," says Govind Rao, a professor of chemical and biochemical engineering and director of the Center for Advanced

ISTOCKPHOTO

Sensor Technology at the University of Maryland, Baltimore County, who was not involved in the study.

For decades, scientists have known that pulse oximeters, devices that estimate blood-oxygen saturation, can be affected by a person's skin color. But prior to the global COVID-19 outbreak, when a spotlight was shone on this disparity, there was little apparent urgency in rectifying the problem. In 2021, the U.S. Food and Drug Administration issued a warning about this limitation of pulse oximeters. The agency says it plans to hold a public meeting of the Medical Devices Advisory Committee later this year, with a focus on pulse oximeters.

To examine how patients with COVID-19 were affected by this flaw in pulse oximeters, Wu and his collaborators looked at medical records from more than 7,000 COVID-19 patients in the Johns Hopkins hospital system, which includes six academic and community hospitals, between March 2020 and November 2021. In the first part of the study, researchers compared blood-oxygen saturation for the 1,216 patients who had measurements taken using both a pulse oximeter and arterial blood-gas analysis, which determines oxygen saturation using direct analysis of blood. The researchers found that the pulse oximeter overestimated blood-oxygen saturation by an average of 1.7 percent for Asian patients, 1.2 percent for Black patients, and 1.1 percent for non-Black Hispanic patients.

The researchers then used these results to create a statistical model to estimate what the arterial blood-gas measurements would have been for patients who had undergone only pulse-oximeter measurements.

To qualify for COVID-19 treatment with remdesivir, an antiviral drug, and dexamethasone, a steroid, patients had to have a blood-oxygen saturation of 94 percent or less. Based on the researchers' model, nearly 30 percent of the 6,673 patients about whom they had enough information to predict their arterial blood-gas measurements had oxygen-saturation levels below this cutoff. Many of these patients, most of whom were Black or Hispanic, had their treatment delayed for between 5 and 7.7 hours; Black patients were delayed, on average, 1 hour more than similarly situated white patients.

There were 451 patients who never qualified for treatments but likely should have, according to the oxygen-saturation figures deduced by the researchers. Of these underserved patients, 54.8 percent were Black, while 27 percent were Hispanic.

The study, says Rao, "shows how urgent it is to move away from pulse [oximeters]" and find alternative ways of measuring blood-oxygen saturation.

Though awareness of pulse oximeters' accuracy issues goes back as far as the 1980s, the medical community had been lax in addressing it. Wu says increasing vigilance helps, but it may be necessary—at least in the short term—to give up the convenience of pulse oximeters in favor of the bias-free results of arterial blood-gas analyses.

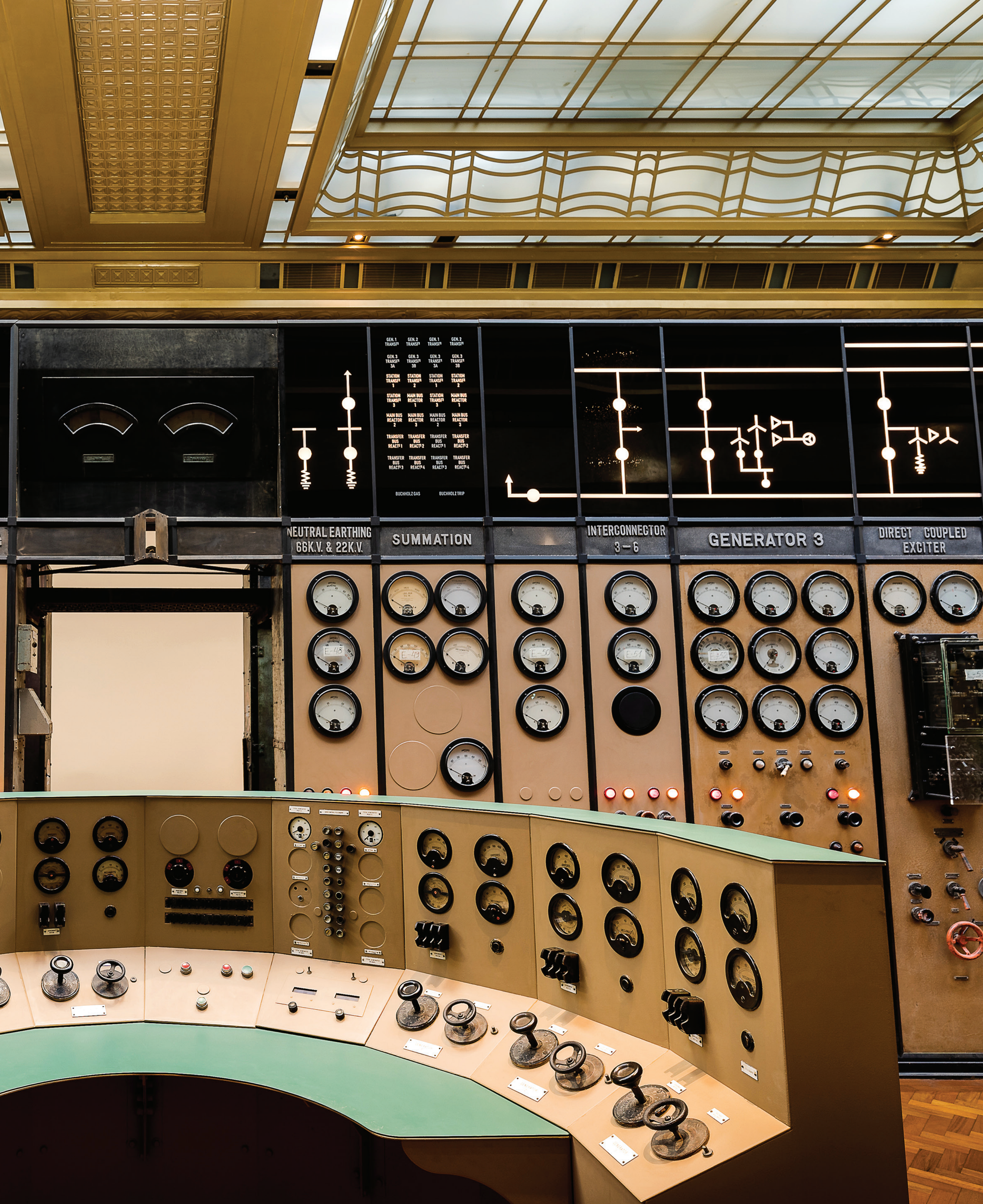
A long-term solution will require changing pulse-oximeter technology, either by using a different method entirely or having devices that can better adjust readouts to account for differences in skin color. One technological alternative is having devices that measure oxygen diffusion across the skin. This technique, called transdermal measurement, is what Rao's lab is currently working on. ■

Revamping an Art Deco Masterpiece

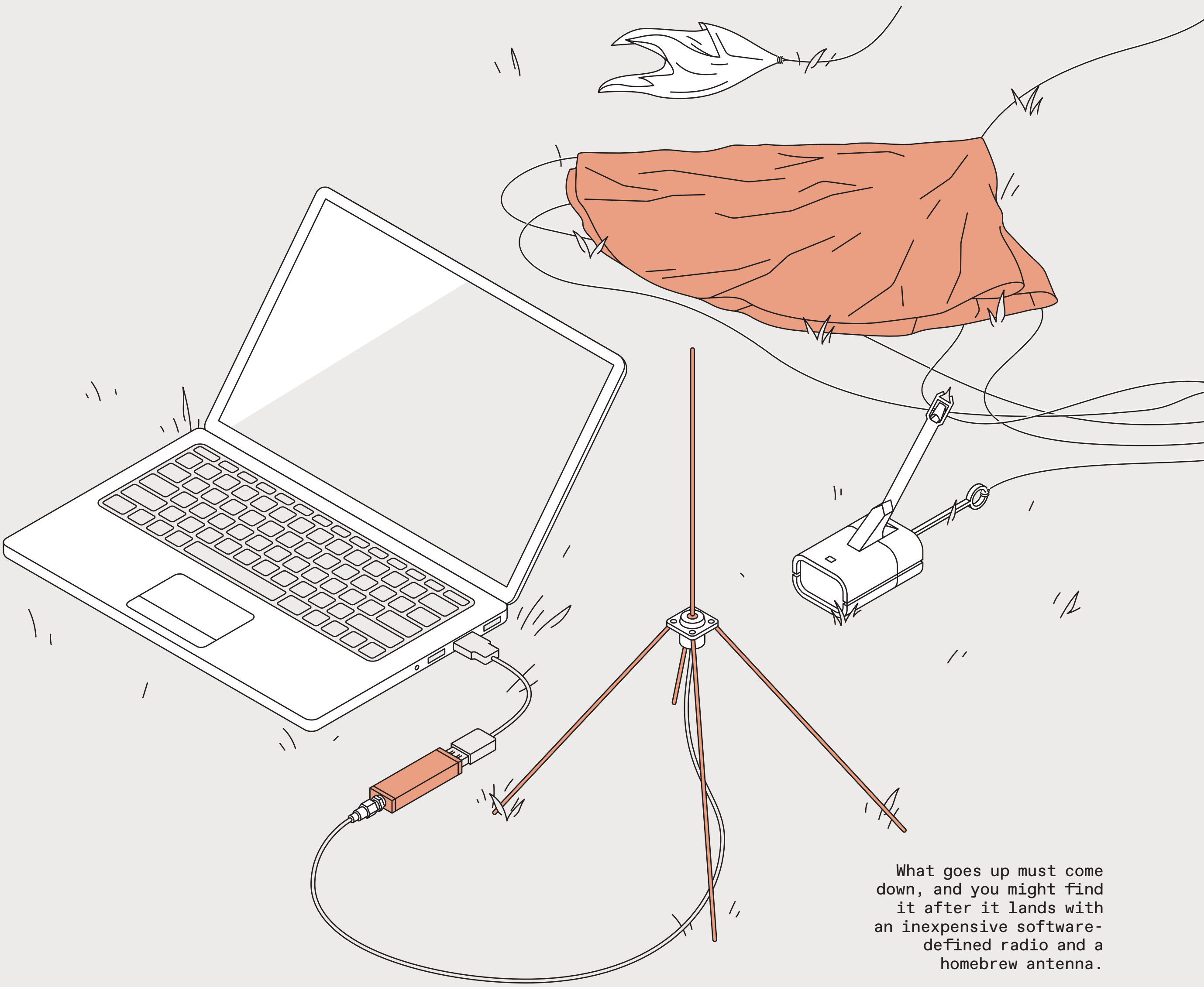
By Willie D. Jones

This beautifully outfitted space is the newly restored Control Room A at the Battersea Power Station in London. For half a century, the electric power hub controlled the flow of current that met one-fifth of London's electricity demand. The hub was decommissioned in 1983. Now it has been returned to its original 1930s Art Deco glory. The painstaking restoration, complete with period details—including the gauges engineers relied on when the station was fully functional-took decades to complete.

PHOTOGRAPH BY JAMES PARSONS


NEUTRAL EARTHING
66K.V. & 22K.V.
SUMMATION
INTERCONNECTOR
3 – 6
GENERATOR 3
DIRECT COUPLED
EXCITER

Hands On



What goes up must come down, and you might find it after it lands with an inexpensive software-defined radio and a homebrew antenna.

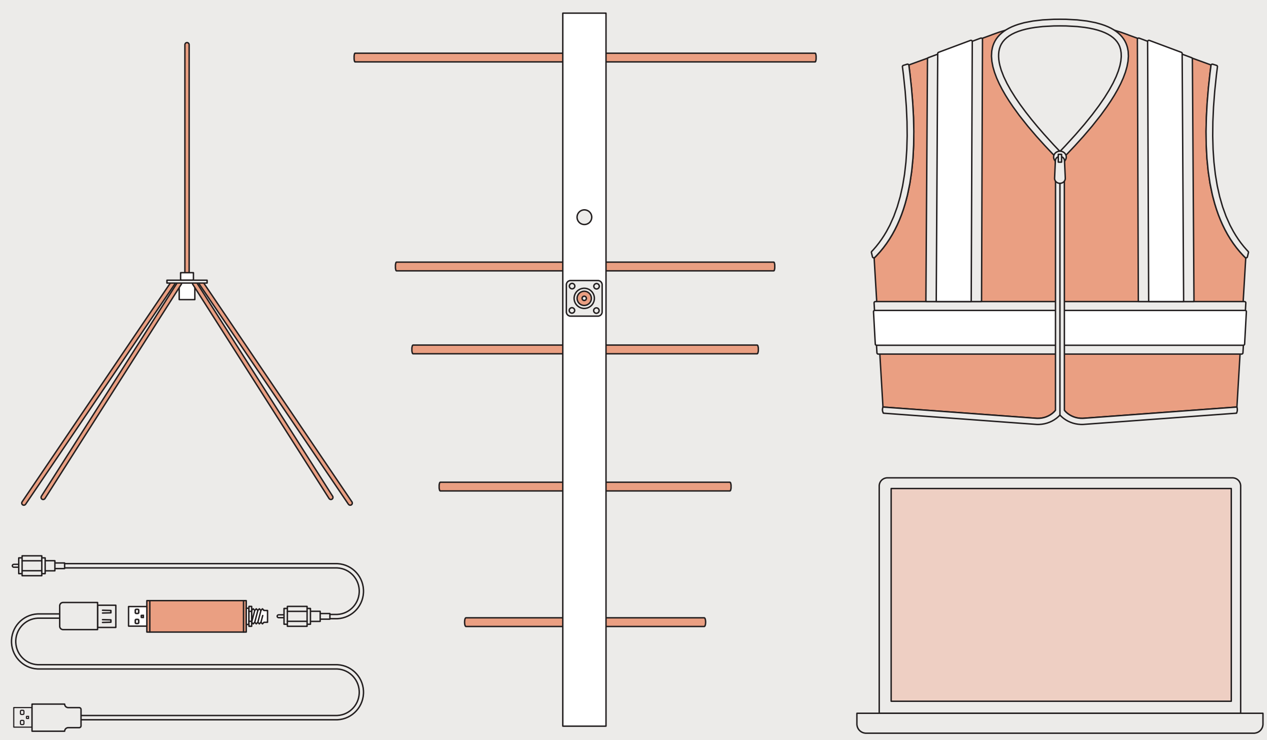
Chasing Downed Weather Balloons › Hunt them with a cheap SDR receiver and a homemade antenna

BY DAVID SCHNEIDER

I've never had an interest in pursuing game such as deer or grouse. Hunting was never my thing. But I do enjoy a good technical challenge. And I recently found a challenge that involves hunting—with downed radiosondes as the quarry.

Radiosondes are instrument packages carried aloft by weather balloons. They measure atmospheric conditions up to altitudes of 30 kilometers or more, providing key data for the computer

Illustrations by James Provost



You can use an inexpensive software-defined-radio dongle [bottom left] to track radiosondes carried aloft by weather balloons. Even a simple omnidirectional antenna [top left] will serve for that, but a Yagi antenna [middle] provides greater sensitivity and directionality. A laptop runs the software used to analyze the signal, and an orange safety vest reassures onlookers.

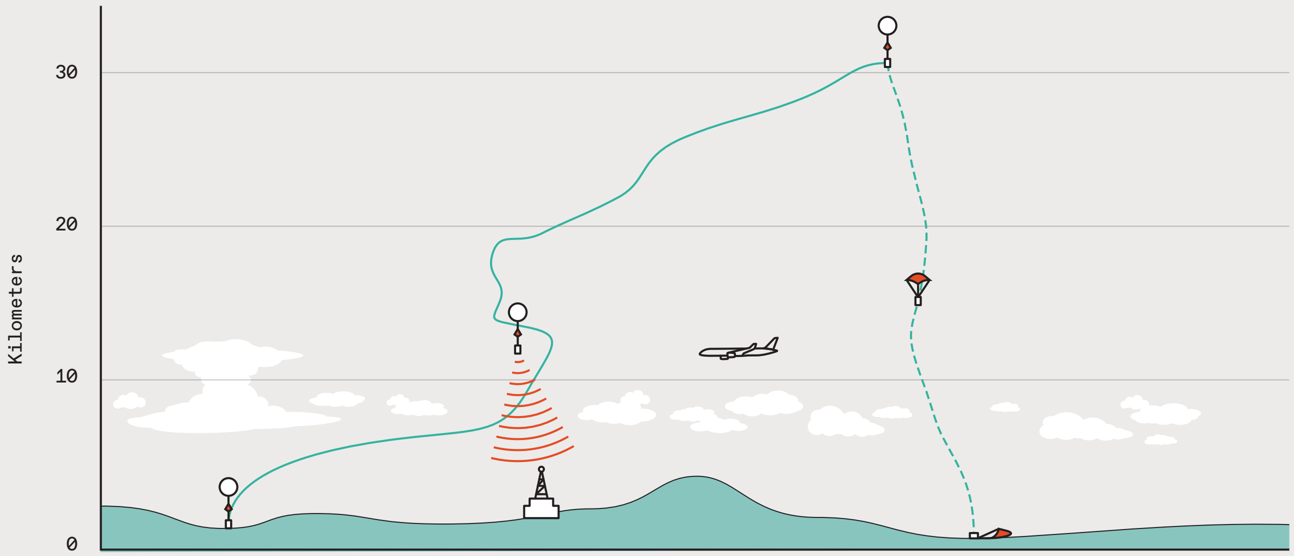
models that give us our weather predictions. Weather services around the world launch countless numbers of these balloons. The U.S. National Weather Service (NWS) alone sends them up twice a day from about 100 different locations. During their flights, which can last as long as a few hours, they transmit data by radio. Eventually the balloons ascend so high that the low pressure causes them to burst. The radiosonde package descends, slowed by a small parachute.

Sometimes these radiosondes are found on the ground. The NWS reuses returned radiosondes when it can. Tracking one down and returning it would be a way for me to say, "Thank you" for the essential work the folks there do. My hunting gear would be a pair of home-made antennas and a software-defined radio (SDR).

Another invaluable aid was the Sondehub Tracker website. It's amazing: You can track the flights of weather balloons around the world in real time using data received by radio amateurs. I've been using this site to follow the balloons launched from the airport in Greensboro, N.C., about 70 km from my home. But the radio amateurs who have been tracking balloons launched from Greensboro are located quite far away, and they typically lose contact when the falling radiosonde reaches a few kilometers' altitude, which leaves considerable uncertainty in its final position.

Clearly, I'd need to track these things myself, following them down as close to the ground as possible. Then I could go to my best guess for the landing site and try to pick up the signal from the downed radiosonde—transmitting perhaps from high in a tree (which would no doubt present its own interesting technical challenges).

If you're wearing an orange vest, everyone assumes that whatever you are doing is legit.



Weather balloons rise into the stratosphere, with their position dictated by wind movements at different altitudes. Each balloon eventually bursts, and the sonde descends by parachute. All the while, the radiosonde transmits telemetry that can be picked up by anyone listening on the right frequency.

The balloon data on the Sondehub site shows that the NWS in Greensboro is using Graw DFM-17 radiosondes, transmitting on 403.4 megahertz. To receive these signals, I quickly cobbled together a 1/4-wave antenna (using an online calculator to size the elements), plugged that into an SDR dongle attached to my laptop, and ran the HDSDR software, which I had used for various other projects. In no time, I was picking up FM signals from the balloons being launched from the Greensboro airport at 7 a.m. and 7 p.m. each day.

It took just a little more work to figure out how to decode these signals so that I could track radiosonde position and altitude. For that, I use a program called Sonde Monitor. A third piece of software, called Virtual Audio Cable, pipes the demodulated FM signal from HDSDR to Sonde Monitor for decoding. So with a decent signal, it's easy to see the geographical coordinates and altitude reported by a radiosonde. Sonde Monitor can also plot the position of the radiosonde on Google Maps.

To further help me in locating a downed radiosonde, I built a directional antenna using a handy website to design a five-element Yagi antenna for 403 MHz. I constructed it using some left-over PVC for the boom and some 1/4-inch-diameter (6-mm) copper tubing that I had in my scrap pile. Despite its origins as junk, it works great.

Last night, 14 August, I saw that the Sondehub Tracker was projecting that the 7 p.m. flight would end in Siler City, just 50 km from my home. (Readers old enough to remember "The Andy Griffith Show" might assume that this is a fictional town, but in fact it's a real place.) So I gathered up my laptop, my antennas, and some food and water for my hunting expedition, along with one more essential piece of equipment: an orange safety vest. I didn't really expect to be taken for a bear and shot while tromping through the woods, but in a past life I used to be a geologist. I learned then that when you pull your car over on the highway and start snooping around, people (including state troopers) tend to think you are up to no good. If you're wearing an orange vest, however, everyone assumes that whatever you are doing is legit.

After 40 minutes' drive, I arrived at a convenient stopping place close to the estimated landing site, which put me in the parking lot of a food-processing facility. The late-shift workers must have wondered what I was doing waving around what must have looked to them like a shrunken TV antenna. From that nearby vantage, I was able to track the radiosonde down to just 200 meters or so above ground level. I then drove 6 km to a church located close to my last position fix. And from the church parking lot, I was easily able to pick up signals from the downed radiosonde, which allowed me to map its final position on Google Maps.

Because it was dark, I headed home, but I returned today in daylight to see whether I could spot the orange parachute and perhaps even retrieve the radiosonde, which had landed just 150 meters from the road. Alas, I was thwarted by some features of the terrain not apparent from Google Maps: a chain-link fence and signs warning that trespassers would be prosecuted. So I didn't bring home any radiosonde trophies today. But one thing worked perfectly during my outings: the orange vest. Not one person so much as asked me what the heck I was doing! ■

Careers

Magdalene Maluta checks over ARC Ride's inventory of electric vehicles, which includes e-bikes, scooters, motorcycles, and *tuktuks*.

Magdalene Maluta >
She's building a fleet of personal EVs in Kenya

BY DANIEL P. DERN

Electric vehicles are gaining in popularity around the world, especially with the high cost of fuel. But some of the current models aren't a good fit for owners who can't wait around for hours for their batteries to charge, such as taxi drivers, delivery people, and ride-hailing services.

One startup trying to solve this problem is ARC Ride, in Nairobi, Kenya.

Founded in 2020, the company sells a variety of EVs, including e-bikes, scooters, motorcycles, and *tuktuks*. ARC Ride is also installing battery-swapping stations around the city and has an app that lets EV owners locate the stations.

A key person involved in the critical tasks of assembling, servicing, and testing the company's vehicles and related products is Magdalene Maluta. The EV enthusiast came to the 20-employee company through a confluence of motivation, the right mix of skills, and fate.

"Before I came to ARC Ride, I had been looking into EVs [as a career choice]," Maluta says. "I would read about Tesla and wish I was one of the people in their videos making the vehicles."

She joined the startup in January 2021. As an inventory and maintenance manager, Maluta is involved in many facets of the company, including supervising the assembly of EVs, overseeing the maintenance and support teams, tracking inventory, and helping to test new features on the mobile app. She is also helping to design and develop the company's next generation of vehicles, batteries, and swap stations.

ARC Ride offers four types of EVs. The E1 is an electric bicycle with a battery range of 60 kilometers and up to 65 km with pedal assist. With the throttle, the top speed is 60 km/h and with pedaling added, it can get up to 65 km/h. The E2 is a two-wheel scooter with a battery range of 85 km and a top speed of 60 km/h. The E2+ all-electric motorcycle, called a *boda-boda*, can accommodate two batteries and gets a range of 85 km with one battery and 160 km with two. Its top speed is 75 km/h. The E3, a three-wheeled *tuktuk* motorized rickshaw, can carry up to 500 kilograms of goods and has a range of 80 km.

The startup has aggressive plans to add more models and increase production and sales, along with adding more swap stations, Maluta says. It also has plans to expand to other cities and neighboring countries.

"We are looking into having a single battery that can be used in all four of our current EVs," she says. "Also, we are looking into increasing our vehicles' range and speed. And—like all EV makers—we want faster battery charging."

Maluta has a hand in hiring people and looks for specific skills. "To design and develop EV products, you have to be able to use tools like AutoCAD, Autodesk, and SolidWorks."

ARC Ride is committed to diversity in its hiring, and Maluta works hard to hire more women for her team. But, she emphasizes, "You have to have the drive and passion for this kind of work, and you need to show it. Do not doubt yourself. Your identity should be the last thing that is going to limit you." ■

Photo by Deco Abdi

Numbers Don’t Lie

Fuel, Food, and War

Energy and grain are part and parcel

The Russian invasion of Ukraine has brought a stream of reports about the country’s energy exports. Here are the basic facts.

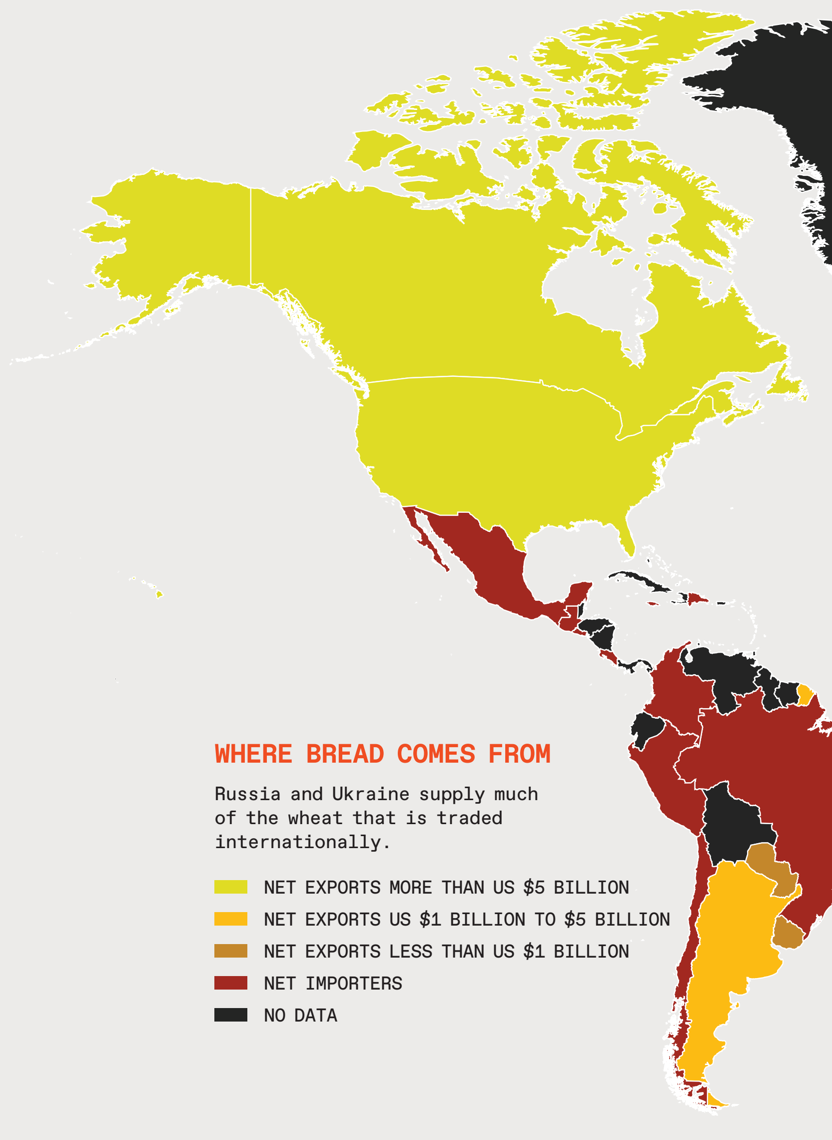
Russia ranks second in the extraction of both crude oil (behind the United States and ahead of Saudi Arabia) and natural gas (behind the United States and ahead of Iran), and it is the sixth-largest producer of coal (behind Australia and ahead of South Africa). Before the war, Russia exported about 55 percent of its fossil-fuel output, mostly to the European Union. The EU bought about 85 percent of the natural gas that Russia shipped out (via pipelines from Western Siberia) and nearly 55 percent of the crude oil and refined oil products that Russia exported (via pipelines and tankers).

This means that in 2021 the EU got more than 40 percent of its natural gas, 27 percent of its oil, and 46 percent of its coal imports from Russia, for which it paid €99 billion, or nearly US $10 billion a month. Since the start of the war, soaring energy prices have lifted this import bill to about $23 billion a month, making the EU a significant de facto financier of the Russian invasion: three-quarters of a billion a day! Belatedly, in May, the EU produced its REPowerEU plan, which is intended to drastically reduce this dependence.

But Russian exports go far beyond fossil fuels; there is also food. It is one thing for the EU to reduce its dependence on Russian hydrocarbons, quite another for many low-income countries to do without Russian (and Ukrainian) grain. This is because Russia has changed from a proverbial agricultural basket case to a food basket. Any attempt to reduce imports of its foodstuffs would impose higher prices on precisely those nations that can least afford them.

The Soviet Union long struggled to produce wheat, and beginning in the 1970s the country indeed began to import the grain en masse from the United States. After the Soviet Union unraveled in the early 1990s, its wheatlands were divided between Russia and Ukraine. Russian agriculture at first shrank, then staged a comeback in the early years of the new century: By 2015 it had begun to export about as much wheat as the United States, and in 2018 it sold nearly twice as much (almost 44 million tonnes), most of it going to the Middle East and Africa. Some of the countries in those regions have also been buying Ukrainian wheat (the country is the fifth-largest exporter of wheat) and sunflower oil, for which Ukraine provides half and Russia a fifth of global exports.

Moreover, thanks to its large natural-gas production, Russia is also the world’s second-largest producer of ammonia (after China, ahead of India),



WHERE BREAD COMES FROM

Russia and Ukraine supply much of the wheat that is traded internationally.

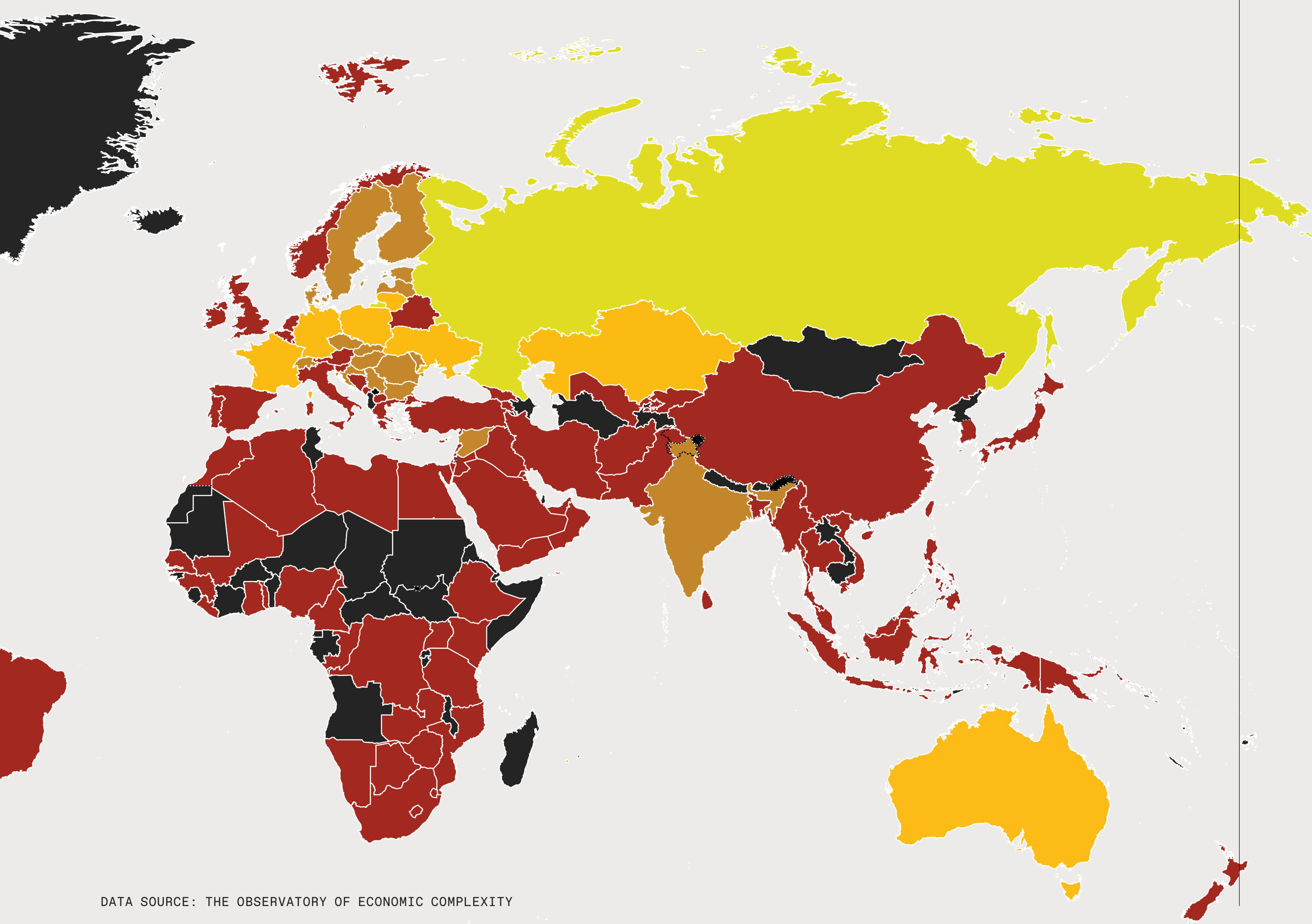
BY VACLAV SMIL

a key ingredient for artificial nitrogenous fertilizers, of which it is the second-largest exporter. Its reserves of potash and phosphates make it, respectively, the world's second-largest producer (and exporter) of potassium (after Canada) and the fourth-largest producer (after China, Morocco, and the United States) of phosphates. No other country controls a similarly large share of each of the three plant macronutrients that are needed to sustain high crop yields.

No wonder the war raised concerns about the near-complete disruption of Ukrainian food exports (Odesa's port was blockaded) and about the reduction of Russia's grain and fertilizer shipments. Global food prices had begun to rise already during the pandemic, and their further expected war-induced increase will have the greatest impact in Asia and Africa, where people often spend 30 to 40 percent of their disposable income on food; the U.S. share in 2020, by contrast, was about 9 percent.

Worst of all, the World Food Programme and the Food and Agriculture Organization of the United Nations now expect that rising food prices, widespread supply problems, and worsening drought in parts of Africa will raise the number of malnourished and hungry people. That is why it was encouraging to hear in late July that Russia and Ukraine had agreed to restart Ukrainian food shipments: The first grain-carrying ship left Odesa, Ukraine's largest port, for Lebanon on 1 August 2022. ■

It is one thing for the EU to reduce its dependence on Russian hydrocarbons, quite another for many low-income countries to do without Russian (and Ukrainian) grain.



DATA SOURCE: THE OBSERVATORY OF ECONOMIC COMPLEXITY

Inside the *Universe* Machine

IEEE SPECTRUM **EXPLORES THE WEBB TELESCOPE'S GROUNDBREAKING ENGINEERING**

The stunning image that President Biden revealed on 11 July [opposite] revealed the power of Webb's 6.5-meter-wide mirror. Too large to fit into any rocket, it was folded up when launched.

On 11 July, President Joe Biden unveiled the first publicly released image from the James Webb Space Telescope. The big announcement came after a nail-biting but thankfully uneventful 198-day journey after the telescope's December launch as it traveled to its destination in deep space. In the interim, Webb had unboxed, unfolded, and unfurled itself as the observatory made its way to a position more distant than the moon and far enough away from Earth to evade stray infrared photons coming from our planet. • The image itself, of a galaxy cluster called SMACS 0723, was a jaw-dropping collection of astrophysical and cosmological desiderata. "You start looking at this image and realize there's no blank sky—there's something crazy happening everywhere," the astronomer B. Scott Gaudi of Ohio State University, in Columbus, told *Space.com*. As can be seen in a dozen or more journal articles already written about the image, Webb essentially unveiled whole new regions of the universe never observed before. • The farthest edges of cosmic distance that the Hubble Space Telescope probed showed light emitted 420 million years after the big bang. Webb blew that door open with its kickoff image alone—by one count resolving at least 88 galaxies beyond Hubble's purview. Moreover, it can theoretically see all the way back into a universe just tens of millions of years old. And this is to say nothing of Webb's equally revolutionary capabilities at observing exoplanets, galactic structure, star formation, objects within our own solar system, and on and on. • How can Webb do all this? What's the groundbreaking engineering that enabled the groundbreaking science this telescope now seems well poised to perform? Two regular *IEEE Spectrum* contributors and one of the magazine's associate editors surveyed the teams at NASA, the European Space Agency, Northrop Grumman, and elsewhere who designed, built, and launched this incredible "universe machine." The story they revealed highlights just how herculean the effort was to construct this portal into cosmic time and astronomical discovery—one that's literally and figuratively beyond the moon. ■

Where No Optics Have Gone Before

"BUILD SOMETHING that will absolutely, positively work." This was the mandate from NASA for designing and building the James Webb Space Telescope—at 6.5 meters wide the largest space telescope in history. Last December, JWST launched successfully. And now it has at long last begun releasing scientific images and data.

Mark Kahan, on JWST's product-integrity team, recalls the engineering challenge of building such a telescope as a call to arms for an army of thousands of people around the world, who set out to create one of the most ambitious scientific instruments in human history. Kahan—chief electro-optical systems engineer at Mountain View, Calif.–based Synopsys—and many others in what Kahan calls JWST's "pit crew" drew hard lessons from three decades ago, having helped repair another world-class space telescope with a debilitating case of flawed optics: the Hubble Space Telescope.

PREVIOUS PAGES, LEFT: CHRIS GUNN/NASA; RIGHT: NASA

DESIREE STOVER/NASA

The James Webb Space Telescope's 18-segment mirror could, in theory, resolve a penny 40 kilometers away or a football 550 km away.

Hubble is in low Earth orbit, so a special space-shuttle mission to install corrective optics was possible. Not so with JWST, which is well out of reach of repair crews.

Why position JWST so far away? That's because its mission is to study the infrared universe, and that requires shielding the telescope and its sensors from both sunlight and the infrared glow of Earth. A good place to do that without going too far afield is an empty patch of interplanetary space 1.5 million kilometers away, well beyond the moon's orbit, near a spot physicists call the second Lagrange point, or L2. JWST circles L2 in what's known as a halo orbit—an orbit around nothing at all.

The pit crew's job was "down at the detail level, error checking every critical aspect of the optical design," says Kahan. Having learned the hard way from Hubble, the crew insisted that every measurement of Webb's optics be made in at least two different ways that could be checked and cross-checked. Diagnostics were built into the process, Kahan says, so that "you could look at them to see what to kick" to resolve any discrepancies. Their work had to be done on the ground, but their tests had to assess how the telescope would work in deep space.

Superficially, Webb follows the design of all large reflecting telescopes. A good-size primary mirror collects light—from stars, galaxies, nebulas, planets, comets, and other astronomical objects—and then focuses those photons onto a smaller secondary mirror. That mirror then sends it to a third one, which ultimately directs the light to instruments that record images and spectra.

Webb's 6.5-meter primary mirror is the first segmented mirror to be launched into space. All the optics had to be made on the ground at room temperature but were deployed in space and operated at 30 to 55 degrees Celsius above absolute zero. "We had to develop three new technologies" to make it work, says Lee Feinberg of the NASA Goddard Space Flight Center, who has managed the optical-telescope element for Webb for the past 20 years.

The longest wavelength that Hubble has to contend with is 2.5 micrometers, whereas Webb is built to observe infrared light that stretches to 28 μm in wavelength. Compared with Hubble, whose primary mirror has an area of 4.5 square meters, Webb's primary mirror "had to be 25 square meters," says Feinberg. Webb also "needed segmented mirrors that were lightweight, and its mass was a huge consideration," he adds. No single-component mirror that could provide the required resolution would have fit on the Ariane 5 rocket that launched JWST. That meant the mirror would have to be made in pieces, folded and secured to withstand the stress of launch, then deployed in space to create a surface that is within tens of nanometers of the shape specified by the designers.

NASA and the U.S. Air Force, which has its own interests in large lightweight space mirrors for surveillance and focusing laser energy, teamed up to develop the technology. The two agencies narrowed eight submitted proposals down to two approaches for building JWST's mirrors. One was based on low-expansion glass made of a mixture of silicon dioxide and titanium dioxide, similar to that used in Hubble. The other uses the light but highly toxic metal beryllium.

The most crucial issue came down to how well the materials could withstand temperature changes from room temperature on the ground to around 50 kelvins in space. Beryllium won because it could fully release stress after cooling without changing its shape and because it's not vulnerable to the cracking that can occur in glass.

JWST has an array of 18 hexagonal beryllium mirrors, each weighing about 20 kilograms. The weight per unit area of JWST's mirror was only 10 percent of that in Hubble. A 100-nanometer layer of pure gold makes the surface reflect 98 percent of incident light over JWST's main observing band of 0.6 to 28.5 μm. "Pure silver has slightly higher reflectivity than pure gold, but gold is more robust," says Feinberg. A thin layer of amorphous silica protects the metal film from damage.

In addition, a wave front–sensing control system keeps the surfaces of these mirror segments aligned to within tens of nanometers. Built on the ground, the system is expected to keep mirror alignment stabilized throughout the telescope's operational life. A backplane holds all 2.4 tonnes of the telescope and instruments rock-steady to within 32 nm.

Hubble's amazing long-exposure images of distant galaxies are possible through the use of gyroscopes and reaction wheels. The gyroscopes are used to sense unwanted rotations, and reaction wheels are used to counteract them.

But the gyroscopes used on Hubble have had a bad track record and have had to be replaced repeatedly. Only three of Hubble's six gyros remain operational today. Hubble also includes magnetic torquers to help it maintain its orientation when needed or to point at different parts of the sky.

Webb uses reaction wheels similarly to turn across the sky, but instead of using mechanical gyros to sense direction, it uses hemispherical resonator gyroscopes, which have no rotating parts. Webb also has a small fine-steering mirror in the optical path, which can tilt only a tiny fraction of a degree. Those very fine adjustments of the light path into the instruments keep the telescope on target. "It's a really wonderful way to go," says Feinberg, adding that it compensates for small amounts of jitter without having to move the whole 6-tonne observatory.

Other optics distribute light from the fine-steering mirror among four instruments, two of which can observe simultaneously. Three instruments have sensors that observe wavelengths of 0.6 to 5 μm, which astronomers call the near-infrared. The fourth, called the Mid-Infrared Instrument (MIRI), observes what astronomers call the mid-infrared spectrum, from 5 to 28.5 μm.

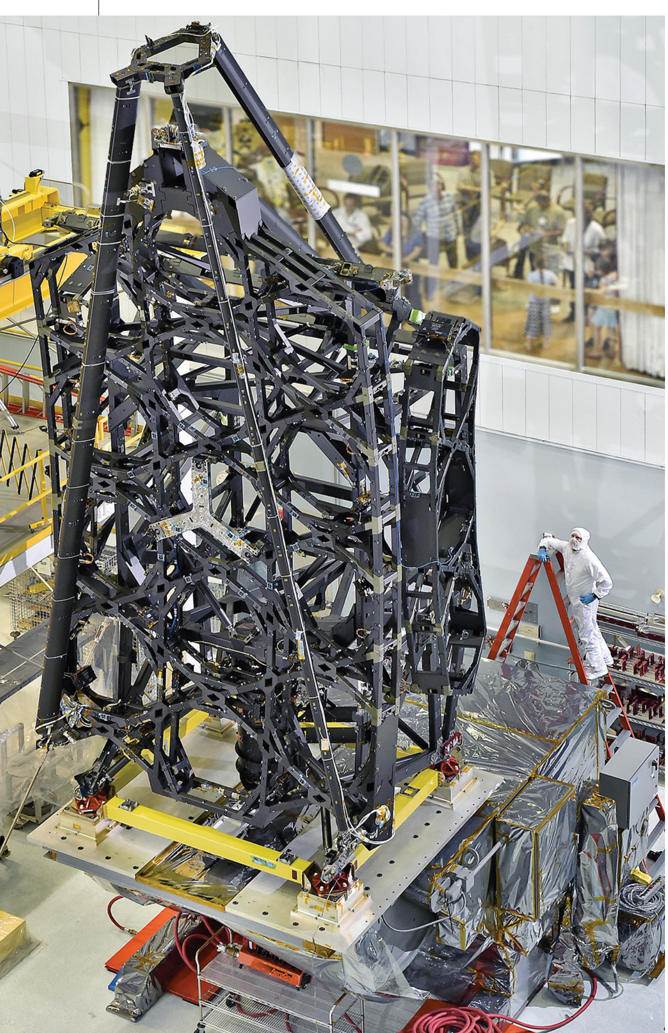
Mid-infrared wavelengths are crucial for observing young stars and planetary systems and the earliest galaxies, but they also pose some of the biggest engineering challenges. Namely, Earth and other planets out to Jupiter glow in the mid-infrared. And for JWST to observe distant astronomical objects, it must avoid recording extraneous mid-infrared noise from all the various sources inside the solar system. "I have spent my whole career building instruments for wavelengths of 5 μm and longer," says MIRI instrument scientist Alistair Glasse of the Royal Observatory, in Edinburgh. "We're always struggling against thermal background."

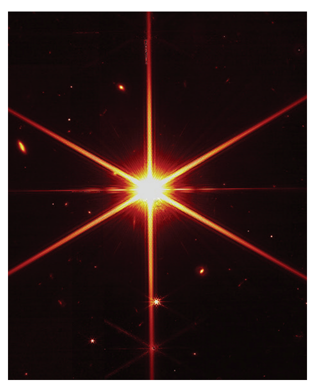
Mountaintop telescopes can see the near-infrared, but observing the mid-infrared sky requires telescopes in space. Even so, the thermal radiation from Earth and its atmosphere can cloud their view, and so can the telescopes themselves unless they are cooled far below room temperature. An ample supply of liquid helium and an orbit far from Earth allowed the Spitzer Space Telescope's primary observing mission to last for almost six years, but once the last of its liquid-helium supply evaporated in 2009, its observations were limited to wavelengths shorter than 5 μm.

Webb has an elaborate solar shield to block sunlight and an orbit 1.5 million km from Earth that can keep the telescope below 55 K, but that's not good enough for low-noise observations at wavelengths longer than 5 μm. The near-infrared instruments operate at 40 K to minimize thermal noise. But for observations out to 28.5 μm, a specially developed closed-cycle helium cryocooler keeps MIRI cooled below 7 K. "We want to have sensitivity limited by the shot noise of astronomical sources," says Glasse, referring to signals that are so weak that each photon creates a detectable peak. That makes MIRI many times as sensitive in the mid-infrared as Spitzer.

Another challenge is the limited transparency of optical materials in the mid-infrared. "We use reflective optics wherever possible," says Glasse, noting that they also pose problems. "Thermal contraction is a big deal," he says, because the instrument was made at room temperature but is used at 7 K. To keep thermal changes uniform and avoid warping, they made the whole structure of gold-coated aluminum.

Detectors are another problem. Webb's near-infrared sen-





Even when performing instrumental calibration tasks, JWST couldn't help but showcase its stunning sensitivity to the infrared sky. The central star [above] is what telescope technicians used to align JWST's mirrors. But notice the distant galaxies in the background.

The JWST backplane [left], the "spine" that supports the entire hexagonal mirror structure and carries more than 2,400 kg of hardware, is readied for assembly with the rest of the telescope.

FAR LEFT: CHRIS GUNN/NASA; LEFT: STSCI/NASA sors use mercury cadmium telluride photodetectors with a resolution of 2,048 by 2,048 pixels. But sensing at MIRI's longer wavelengths required more exotic detectors, ones limited to 1,024 by 1,024 pixels.

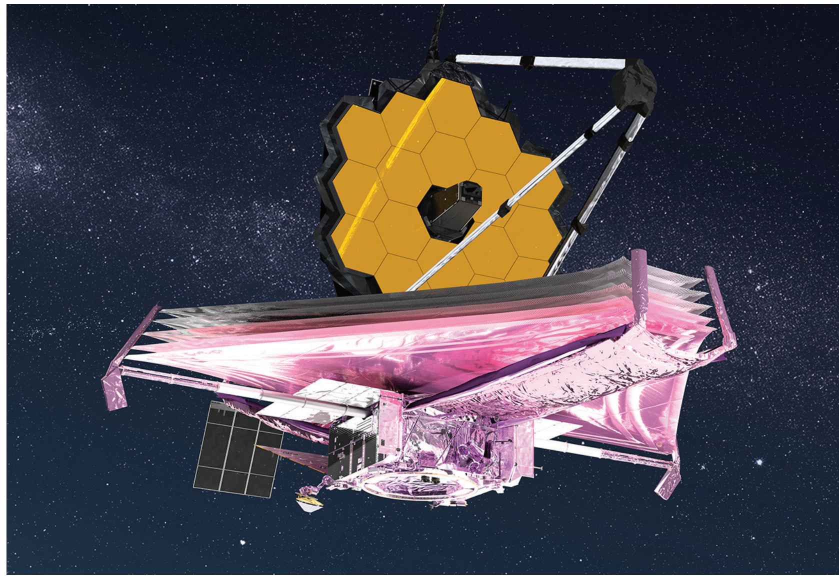
The near-infrared detectors and optical materials used for observing at wavelengths shorter than 5 μm are much more mature than those for the mid-infrared, so the Near-Infrared Camera (NIRCam) does double duty by both recording images and aligning all the optics in the whole telescope. That alignment was the trickiest part of building the instrument, says NIRCam principal investigator Marcia Rieke, of the University of Arizona.

Alignment means getting all the light collected by the primary mirror to the right place in the final image. That's crucial for Webb, because it has 18 separate segments that have to overlay their images perfectly.

Building a separate alignment system would have added to both the weight and cost of Webb, Rieke realized, and in the original 1995 plan for the telescope she proposed designing NIRCam so it could align the telescope optics once it was up in space, as well as record images. "The only real compromise was that it required NIRCam to have exquisite image quality," says Rieke, wryly.

For Feinberg, "commissioning has been a magical five months." When NASA recorded a test image of a single star after Webb first unfurled its primary mirror, it showed 18 separate bright spots, one from each segment. When alignment was completed on 11 March, the image from NIRCam showed a single star with six spikes caused by diffraction. "Everything had to work to get it to [focus] that well," he says. It's been an intense time, but for Feinberg, a veteran of the Hubble-repair mission, commissioning Webb was "a piece of cake."

NASA announced that between 23 and 25 May, one segment of the primary mirror had been dinged by a micrometeorite bigger than the agency had expected when it analyzed the potential results of such impacts. "Things do degrade over time," Feinberg said. But he added that Webb had been engineered to minimize damage, and NASA said the event had not affected Webb's operational schedule. –JEFF HECHT



This artist's rendering shows the James Webb Space Telescope and its five-layer sun shield [in pink and purple, for illustrative purposes only], which keeps the instrument forever in the shade. This isn't how JWST would actually look, of course, because the mirrors and mirror assemblies are by design always shrouded in darkness.

NORTHROP GRUMMAN/NASA

How to Beat the Heat

WHEN APOLLO ASTRONAUTS sent back the first pictures of Earth as a disk in space, the poet Archibald MacLeish wrote of it as "that bright loveliness in the eternal cold." He was not far off. Deep space has a temperature of 2.7 K—just 2.7 degrees Celsius above absolute zero.

The James Webb Space Telescope works—which is to say it's able to look so far out and therefore so far back in time that it can see the first galaxies forming after the big bang—because it can image objects so faint that they barely stand out from the cold around them. That this indeed works as expected became clear when JWST released its first set of images on 12 July.

How did the engineers and designers of this massive telescope ever make it possible to cool the telescope down enough to do its job?

After more than 25 years' work and technological hurdles beyond counting, the Webb team has launched and stationed its mammoth observatory in solar orbit—and brought its instruments below 40 K (–233 °C), cold enough to see the early universe more than 13.5 billion years ago. Remarkably, most of the cooling has been done passively, by shielding the telescope from the sun and letting physics take care of the rest.

"Webb is not just the product of a group of people. It's not the product of some smart astronomers—Webb is truly the product of our entire world's capability," says Keith Parrish, a leader on the Webb team at NASA's Goddard Space Flight Center, in Maryland. "Taken as a whole, Webb is truly the result of our entire know-how of how to build complex machines."

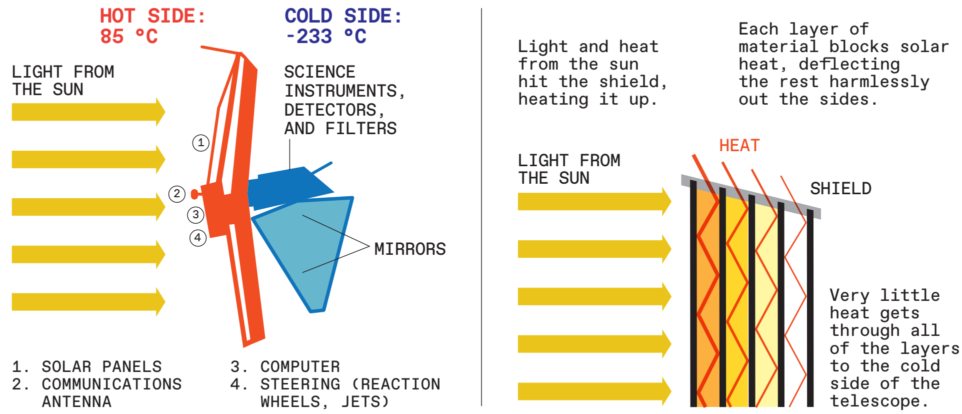
Parrish joined the project in 1997, ultimately becoming its commissioning manager through the years of design, assembly, testing, delay, and finally, launch on 25 December 2021. He says almost everything about the telescope was dictated by the need to have an observatory that would survive for years at supercold temperatures.

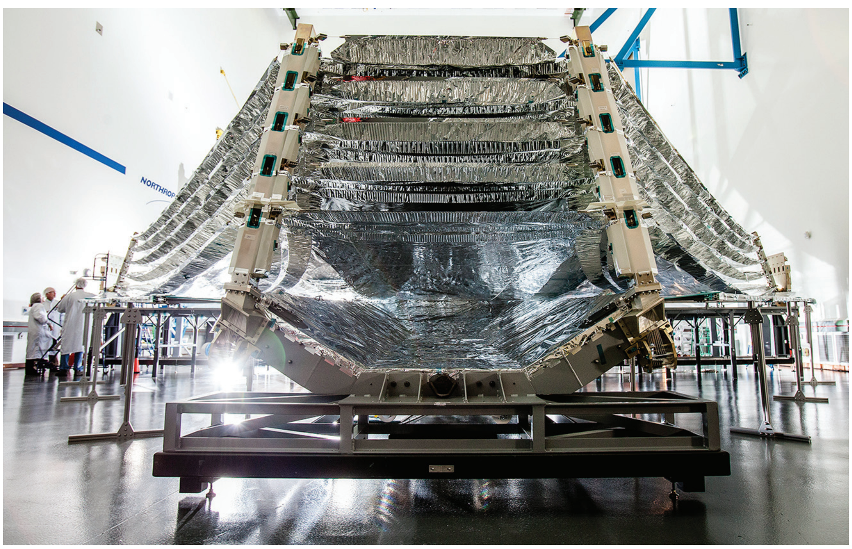
Webb is an infrared observatory for many reasons, not the least of which is that as the universe expands, the wavelength of light from distant objects is lengthened, causing dramatic redshift. Infrared is also good for seeing through cosmic dust and gas, and for imaging cold things such as comets, Kuiper Belt objects, and perhaps planets orbiting other stars.

But anything that is warm gives off

LIKE NIGHT AND DAY

Temperatures on opposite sides of the observatory are vastly different, thanks to a five-layer thermal shield that is the size of a tennis court.





Here, the five-layered JWST sun shield is unfurled and inspected in a clean room. The layers of coated Kapton E never touch, minimizing the transmission of heat from one layer to the next.

infrared radiation. If, like the Hubble Telescope, it were in low Earth orbit, most of its targets would be drowned out by the sun and ground, and by heat in the telescope itself.

"If my signal is heat—and infrared is heat—then what I can't have is other heat sources that are noise in the system," says Jim Flynn, the sun-shield manager at Northrop Grumman, the prime contractor for Webb.

So Webb has been sent to orbit a spot in deep space called L2, 1.5 million kilometers away, opposite the sun, one of the locations known as Lagrange points. The gravity of Earth and the sun combine to allow an object there to circle the sun once per year even though it's farther from the sun than Earth, where objects normally have longer orbital periods. It's a good compromise: Earth is distant enough that it doesn't interfere with observations, but close enough that communication with the spacecraft can be relatively fast. And because the ship isn't flying from day to night and back in orbit around Earth, its temperature is relatively stable. All it needs is a really, really good sunshade.

The design makes for an ungainly looking ship, though. The telescope assembly is intentionally open to space to prevent heat buildup. It's attached to its silvery sun shield, about 14 meters wide and 21 meters long, with five layers of insulating film.

The sun shield resembles a slender kite. The elongated shape, engineers found, would be the most efficient way to keep Webb's optics out of the sun. They considered a square or octagon, but the final version covers more area without much more mass. "It's no larger than it needs to be to meet the science field-of-view requirements, and that unique kite shape is the result," says Parrish.

The shield's five layers are made of Kapton E, a plastic film first developed by DuPont in the 1960s and used for spacecraft insulation and printed circuits. The layers are coated in aluminum and silicon. Each is thinner than a human hair. But engineers knew that, together, they'd be very effective in blocking the sun's heat. The first layer reduces its strength by about an order of magnitude (or 90 percent), the second layer removes another order of magnitude, and so on. The layers never touch, and they're slightly flared from the center of the shield to the periphery so that heat will escape out the sides.

The result: Temperatures on the sunny side of the shield approach 360 K (87 °C), but on the dark side they're below that all-important 40 K (–233 °C). Or, put another way: More than 200 kilowatts of solar energy fall on the first layer, but only 23 milliwatts make it all the way through the fifth.

The ability to cool the telescope passively, first calculated in the 1980s to be possible, was a major advance. It meant Webb would not have to rely entirely on cryogenic cooling apparatus, with refrigerants that could leak and shorten the mission. Of its four main scientific instruments, only one, a mid-infrared detector called MIRI, needs to be cooled to 6.7 K. It's chilled by a multistage cryocooler, which pumps cold helium gas through pulse tubes to draw heat away from the instrument's sensor. It uses the

TOP: IEEE SPECTRUM; BOTTOM: ALEX EVERS/NORTHROP GRUMMAN

Joule-Thomson effect, reducing the temperature of the helium by making it expand after it's forced through a 1-millimeter valve. Pressure comes from two pistons—the cryocooler system's only moving parts—facing opposite directions so that their movements cancel each other out and do not disturb observations.

Building the telescope proved immensely complicated; it fell years behind while its budget ballooned toward US $10 billion. The sun shield needed lengthy redesign after testing, when Kapton tore and fasteners came loose.

"We just bit off way more than we could chew," Parrish says now. "That's exactly what NASA should be doing. It should be pushing the envelope."

Now it's finally deployed, sending data, and surprising engineers who expected at least some failures as it began to operate. Parrish, his work done, is moving on to other projects at Goddard. "I think Webb is just a great product of what it means to be an advanced civilization." –NED POTTER

Beaming Down the Data

THE WEBB TELESCOPE'S images are the by-product of carefully crafted mirrors and finely tuned scientific instruments. But all of its data-collecting prowess would be of little value without an appropriate communications system.

Webb's comms aren't flashy. Rather, the data and communication systems are designed to be incredibly, unquestionably reliable, although some aspects of them are relatively new—it's the first mission to use K_a-band frequencies for such high data rates so far from Earth, for example.

Being so far away from Earth means that data has a long way to travel to make it back in one piece. It also means the communications system needs to be reliable, because the prospect of a repair mission being sent to address a problem is, for the near term at least, highly unlikely. Given the cost and time involved, says Michael Menzel, the mission systems engineer for JWST, "I would not encourage a rendezvous and servicing mission unless something went wildly wrong."

According to Menzel, who has worked on JWST in some capacity for more than 20 years, the plan has always been to use well-understood K_a-band frequencies (a portion of the broader K-band) for the bulky transmissions of scientific data. Specifically, JWST is transmitting data back to Earth on a 25.9-gigahertz channel at up to 28 megabits per second.

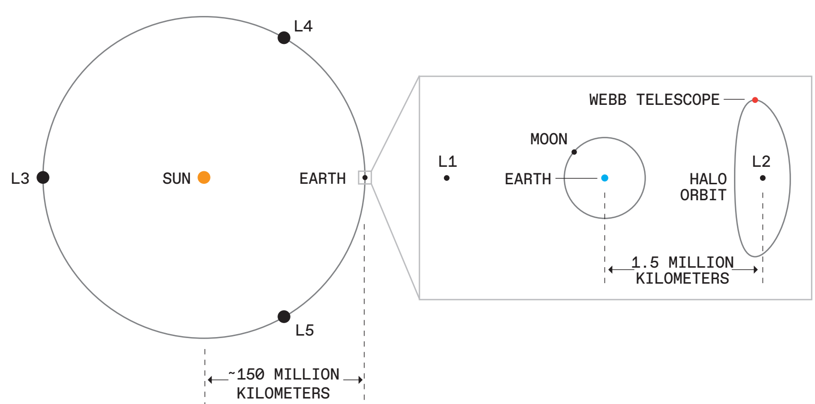
Both the data-collection and transmission rates of JWST dwarf those of the older Hubble Space Telescope, which generates 1 to 2 gigabytes of data daily, whereas JWST can produce up to 57 GB each day.

K_a-band frequencies can transmit more data than X-band (7 to 11.2 GHz) or S-band (2 to 4 GHz), common choices for craft in deep space. So that's a plus. In addition, according to Carl Hansen, a flight-systems engineer at the Space Telescope Science Institute (the science operations center for JWST), a comparable X-band antenna would be so large that the spacecraft would have trouble remaining steady for imaging.

Although the 25.9-GHz K_a-band frequency is the telescope's workhorse communication channel, it also employs two channels in the S-band. One is the 2.09-GHz uplink that ferries future-transmission and scientific-observation schedules to the telescope at 16 kilobits per second. The other is the 2.27-GHz, 40-kb/s downlink over which the telescope transmits engineering data—including its operational status, systems health, and other

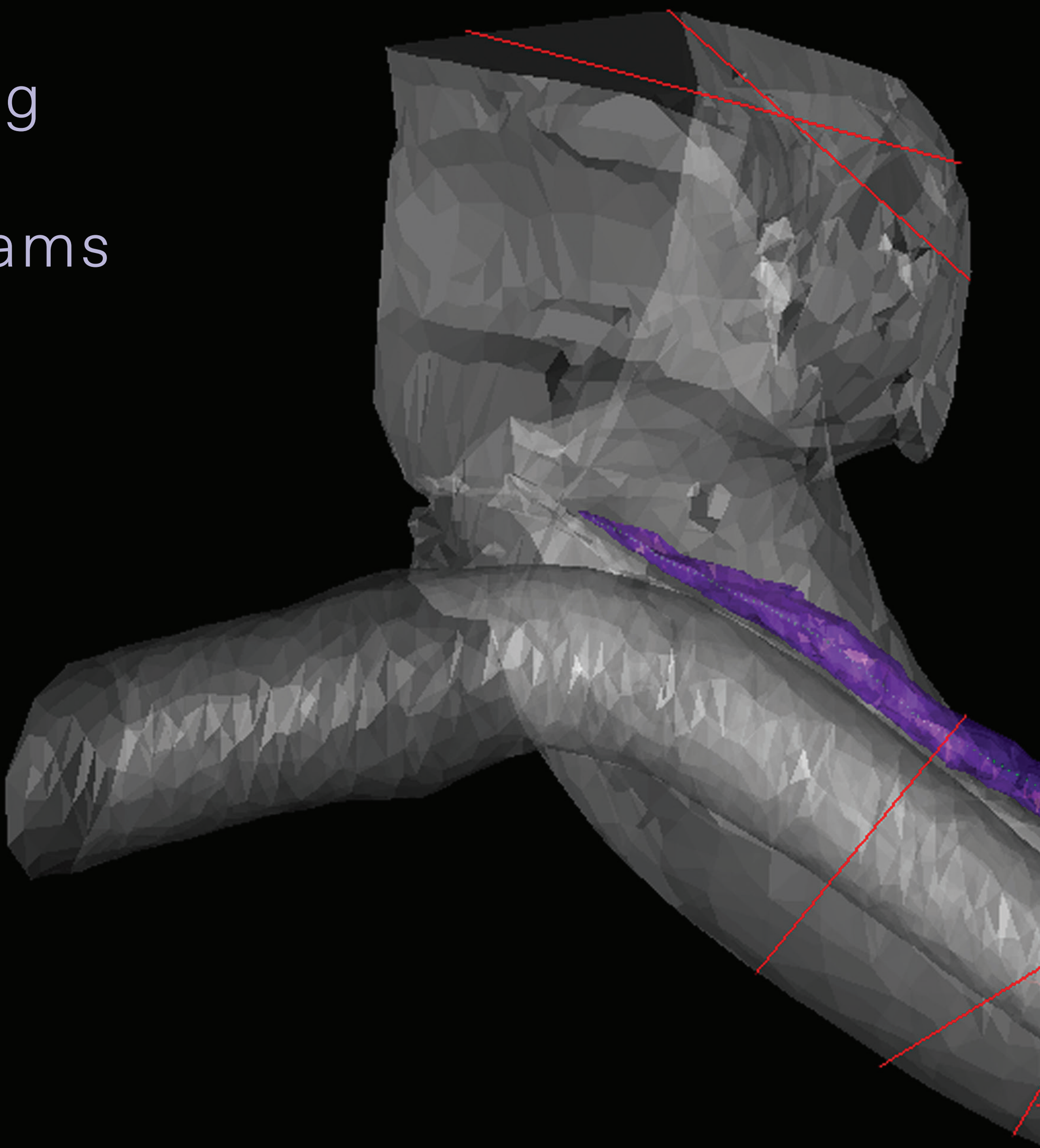
CONTINUED ON PAGE 48

Technicians at Northrop Grumman Aerospace Systems facilities [above] in Redondo Beach, Calif., work on a mock-up of the JWST spacecraft bus—the home of the observatory's power, flight, data, and communications systems. The Earth-sun Lagrange points [below] are equilibrium locations where competing gravitational tugs on an object do not disturb its once-a-year orbit around the sun. JWST is one of three craft currently orbiting L2.



TOP: NASA; BOTTOM: IEEE SPECTRUM

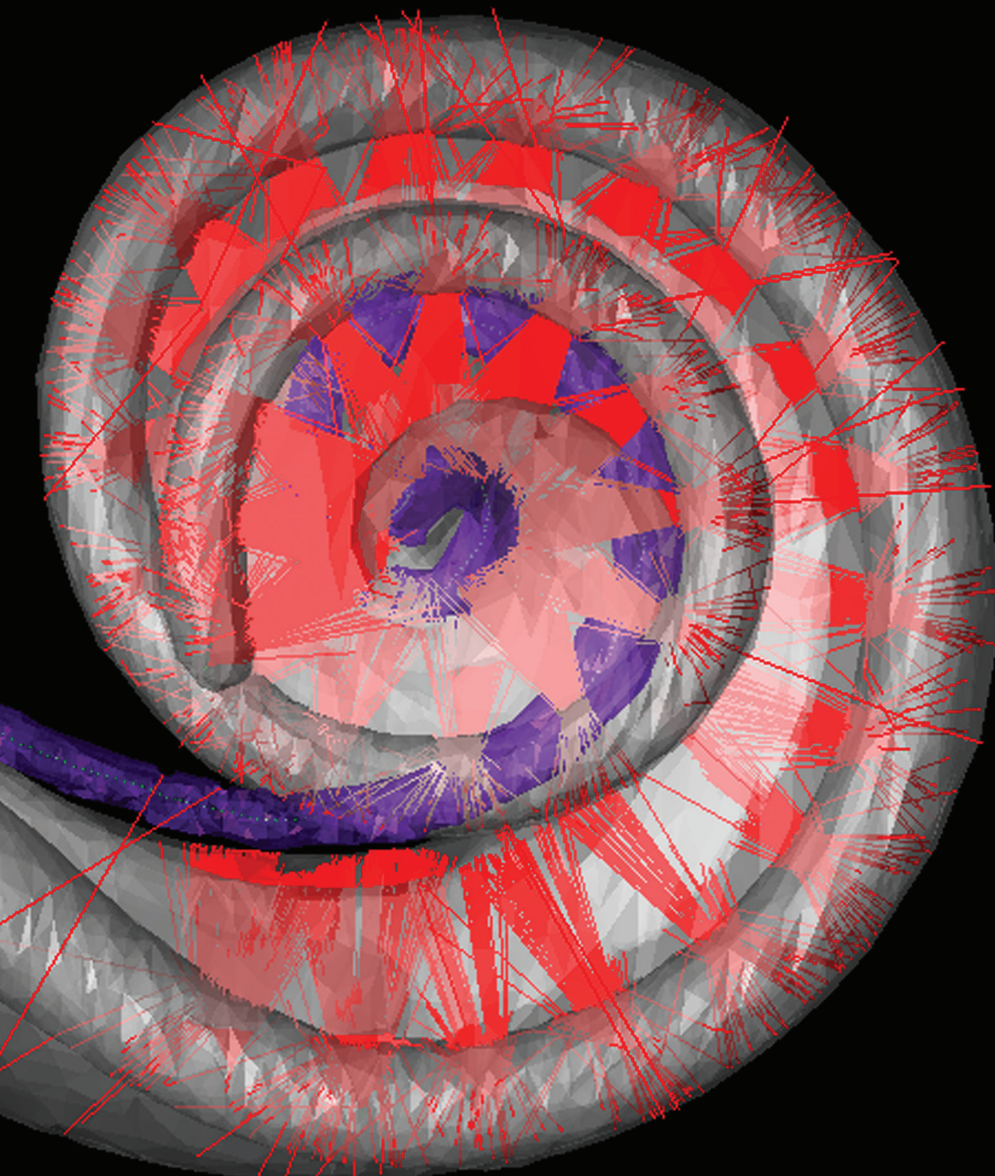
Restoring Hearing With Beams of Light



GENE THERAPY AND OPTOELECTRONICS COULD RADICALLY UPGRADE

There's a popular misconception that cochlear implants restore natural hearing. In fact, these marvels of engineering give people a new kind of "electric hearing" that they must learn how to use.

Natural hearing results from vibrations hitting tiny structures called hair cells within the cochlea in the inner ear. A cochlear implant bypasses the damaged or dysfunctional parts of the ear and uses electrodes to directly stimulate the cochlear nerve, which sends signals to the brain. When my hearing-impaired patients have their cochlear implants turned on for the first time, they often report that voices sound flat and robotic and that background noises blur together and drown out voices. Although users can have many sessions with technicians to adjust their implants' settings to make sounds more pleasant and helpful, there's a limit to what can be achieved with today's technology.



Human hearing depends on the cochlea, a snail-shaped structure in the inner ear. A new kind of cochlear implant for people with disabling hearing loss would use beams of light [red] to stimulate the neurons of the cochlear nerve [inside the purple band].

HEARING FOR MILLIONS OF PEOPLE

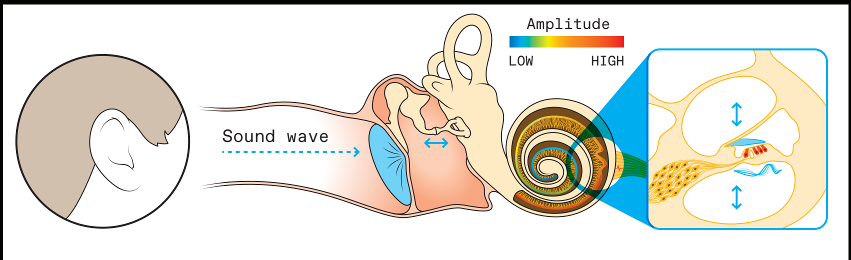
By Tobias Moser

I have been an otolaryngologist for more than two decades. My patients tell me they want more natural sound, more enjoyment of music, and most of all, better comprehension of speech, particularly in settings with background noise—the so-called cocktail party problem. For 15 years, my team at the University of Göttingen, in Germany, has been collaborating with colleagues at the University of Freiburg and beyond to reinvent the cochlear implant in a strikingly counterintuitive way: using light.

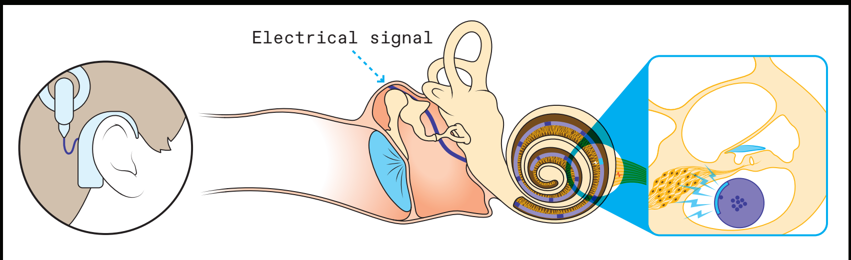
We recognize that today's cochlear implants run up against hard limits of engineering and human physiology. So we're developing a new kind of cochlear implant that uses light emitters and genetically altered cells that respond to light. By using precise beams of light instead of electrical current to stimulate the cochlear nerve, we expect our optical cochlear implants to better replicate the full spectral nature of sounds and better mimic natural hearing. We aim to start clinical trials in 2026 and, if all goes well, we could get regulatory

Three Ways to Hear

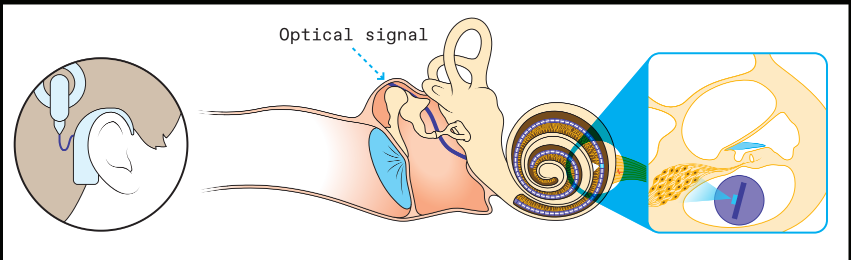
Normal hearing: In normal hearing, sound waves travel down the ear canal and vibrate the eardrum and tiny bones in the middle ear. Those vibrations then reach the spiral-shaped cochlea and move bundles of sensory hair cells. When the hair cells respond, it triggers a neural signal that travels up the cochlear nerve to the brain. Hair cells at the base of the spiral respond to high-pitched sounds; those at the tip respond to low-pitched sounds.



Electrical hearing: With an electrical cochlear implant, a microphone, processor, and transmitter are worn behind the ear. The processor translates a sound's pattern of frequencies into a crude stimulation pattern, which is transmitted to an implanted receiver and then to an electrode array that spirals through the cochlea. A limited number of electrodes (12 are shown here) directly stimulate the cells of the cochlear nerve. But each electrical pulse spreads out, which can stimulate off-target nerve cells and result in muddier sound.



Optical hearing: In a future optical cochlear implant, the external hardware could remain the same, though the processor could break up the sound into narrower frequency bands and transmit a more sophisticated stimulation pattern. The light source, either a flexible microLED array or optical fibers, would spiral through the cochlea, and the implant could have many more stimulation sites, because light is more easily confined in space than electrical current is. The user would have a gene-therapy treatment to make the cells of the cochlear nerve responsive to light, which would trigger precise signals that travel up the nerve to the brain.



approval for our device at the beginning of the next decade. Then, people all over the world could begin to hear the light.

Some 466 million people worldwide suffer from disabling hearing loss that requires intervention, according to the World Health Organization. Hearing loss mainly results from damage to the cochlea caused by disease, noise, or age and, so far, there is no cure. Hearing can be partially restored by hearing aids, which essentially provide an amplified version of the sound to the remaining sensory hair cells of the cochlea. Profoundly hearing-impaired people benefit more from cochlear implants, which, as mentioned above, skip over dysfunctional or lost hair cells and directly stimulate the cochlear, or auditory, nerve.

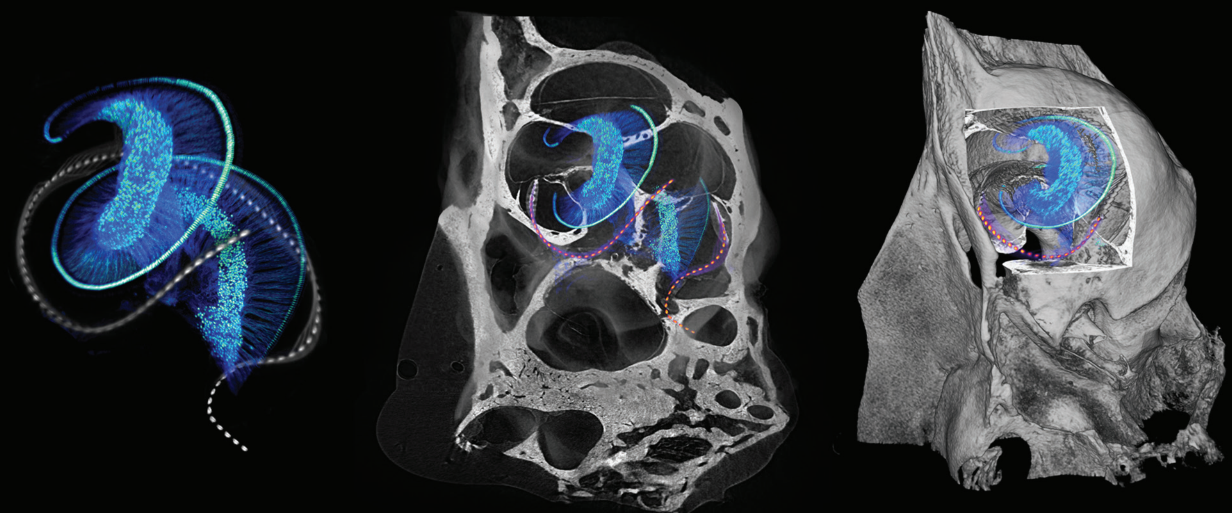
Today's cochlear implants are the most successful neuroprosthetic to date. The first device was approved by the U.S. Food and Drug Administration in the 1980s, and nearly 737,000 devices had been implanted globally by 2019. Yet they make limited use of the neurons available for sound encoding in the cochlea. To understand why, you first need to understand how natural hearing works.

In a functioning human ear, sound waves are channeled down the ear canal and set the eardrum in motion, which in turn vibrates tiny bones in the middle ear. Those bones transfer the vibrations to the inner ear's cochlea, a snail-shaped structure about the size of a pea. Inside the fluid-filled cochlea, a membrane ripples in response to sound vibrations, and those ripples move bundles of sensory hair cells that project from the surface of that membrane. These movements trigger the hair cells to release neurotransmitters that cause an electrical signal in the neurons of the cochlear nerve. All these electrical signals encode the sound, and the signal travels up the nerve to the brain. Regardless of which sound frequency they encode, the cochlear neurons represent sound intensity by the rate and timing of their electrical signals: The firing rate can reach a few hundred hertz, and the timing can achieve submillisecond precision.

Hair cells in different parts of the cochlea respond to different frequencies of sound, with those at the base of the spiral-shaped cochlea detecting high-pitched sounds of up to about 20 kilohertz, and those at the top of the spiral detect-

PREVIOUS PAGES: LAKSHAY KHURANA AND DANIEL KEPPELER

Illustration by Chris Philpot



These 3D microscopic images of mouse ear anatomy show optical implants [dotted lines] twisting through the intricate structure of a normal cochlea, which contains hair cells; in deafness, these cells are lost or damaged. At left, the hair cells [light blue spiral] connect to the cochlear nerve cells [blue filaments and dots]. In the middle and right images, the bony housing of the mouse cochlea surrounds this delicate arrangement.

ing low-pitched sounds down to about 20 Hz. This frequency map of the cochlea is also available at the level of the neurons, which can be thought of as a spiraling array of receivers. Cochlear implants capitalize on this structure, stimulating neurons in the base of the cochlea to create the perception of a high pitch, and so on.

A commercial cochlear implant today has a microphone, processor, and transmitter that are worn on the head, as well as a receiver and electrodes that are implanted. It typically has between 12 and 24 electrodes that are inserted into the cochlea to directly stimulate the nerve at different points. But the saline fluid within the cochlea is conductive, so the current from each electrode spreads out and causes broad activation of neurons across the frequency map of the cochlea. Because the frequency selectivity of electrical stimulation is limited, the quality of artificial hearing is limited, too. The natural process of hearing, in which hair cells trigger precise points on the cochlear nerve, can be thought of as playing the piano with your fingers; cochlear implants are more equivalent to playing with your fists. Even worse, this large stimulation overlap limits the way we can stimulate the auditory nerve, as it forces us to activate only one electrode at a time.

The idea for a better way began back in 2005, when I started hearing about a new technique being pioneered in neuroscience called optogenetics. German researchers were among the first to discover light-sensitive proteins in algae that regulated the flow of ions across a cellular membrane. Then, other research groups began experimenting with taking the genes that coded for such proteins and using a harmless viral vector to insert them into neurons. The upshot was that shining a light on these genetically altered neurons could trigger them to open their voltage-gated ion channels and thus fire, or activate, allowing researchers to directly control living animals' brains and behaviors. Since then, optogenetics has become a significant tool in neuroscience research, and clinicians are experimenting with medical applications including vision restoration and cardiac pacing.

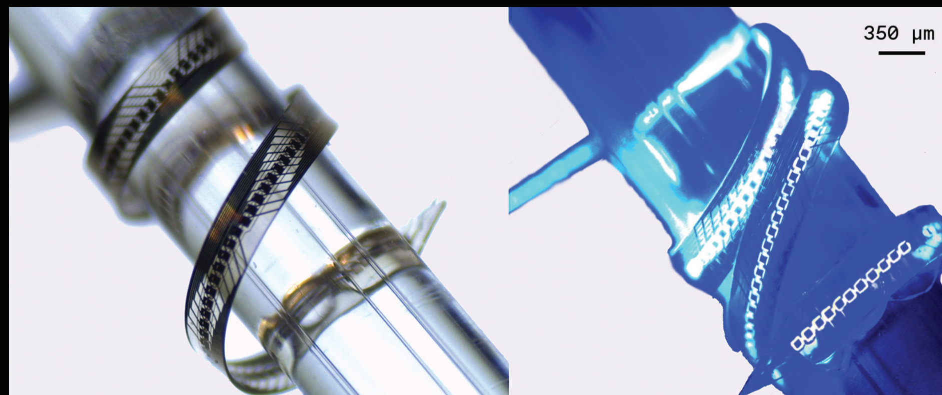
I've long been interested in how sound is encoded and how this coding goes wrong in hearing impairment. It occurred to me that stimulating the cochlear nerve with light instead of electricity could provide much more precise control, because light can be tightly focused even in the cochlea's saline environment.

If we used optogenetics to make cochlear nerve cells light sensitive, we could then precisely hit these targets with beams of low-energy light to produce much finer auditory sensations than with the electrical implant. We could theoretically have more than five times as many targets spaced throughout the cochlea, perhaps as many as 64 or 128. Sound stimuli could be electronically split up into many more discrete frequency bands, giving users a much richer experience of sound. This general idea had been taken up earlier by Claus-Peter Richter from Northwestern University, who proposed directly stimulating the auditory nerve with high-energy infrared light, though that concept wasn't confirmed by other laboratories.

Our idea was exciting, but my collaborators and I saw a host of challenges. We were proposing a new type of implanted medical device that would be paired with a new type of gene therapy, both of which must meet the highest safety standards. We'd need to determine the best light source to use in the optogenetic system and how to transmit it to the proper spots in the cochlea. We had to find the right light-sensitive protein to use in the cochlear nerve cells, and we had to figure out how best to deliver the genes that code for those proteins to the right parts of the cochlea.

But we've made great progress over the years. In 2015, the European Research Council gave us a vote of confidence when it funded our "OptoHear" project, and in 2019, we spun off a company called OptoGenTech to work toward commercializing our device.

DANIEL KEPPELER



This flexible microLED array, fabricated at the University of Freiburg, is wrapped around a glass rod that's 1 millimeter in diameter. The array is shown with its 144 diodes turned off [left] and operating at 1 milliamp [right].

UNIVERSITY OF FREIBURG/FRONTIERS

Our early proof-of-concept experiments in mice explored both the biology and technology at play in our mission. Finding the right light-sensitive protein, or channelrhodopsin, turned out to be a long process. Many early efforts in optogenetics used channelrhodopsin-2 (ChR2), which opens an ion channel in response to blue light. We used it in a proof-of-concept experiment in mice that demonstrated that optogenetic stimulation of the auditory pathway provided better frequency selectivity than electrical stimulation did.

In our continued search for the best channelrhodopsin for our purpose, we tried a ChR2 variant called calcium translocating channelrhodopsin (CatCh) from the Max Planck Institute of Biophysics lab of Ernst Bamberg, one of the world pioneers of optogenetics. We delivered CatCh to the cochlear neurons of Mongolian gerbils using a harmless virus as a vector. We next trained the gerbils to respond to an auditory stimulus, teaching them to avoid a certain area when they heard a tone. Then we deafened the gerbils by applying a drug that kills hair cells and inserted a tiny optical cochlear implant to stimulate the light-sensitized cochlear neurons. The deaf animals responded to this light stimulation just as they had to the auditory stimulus.

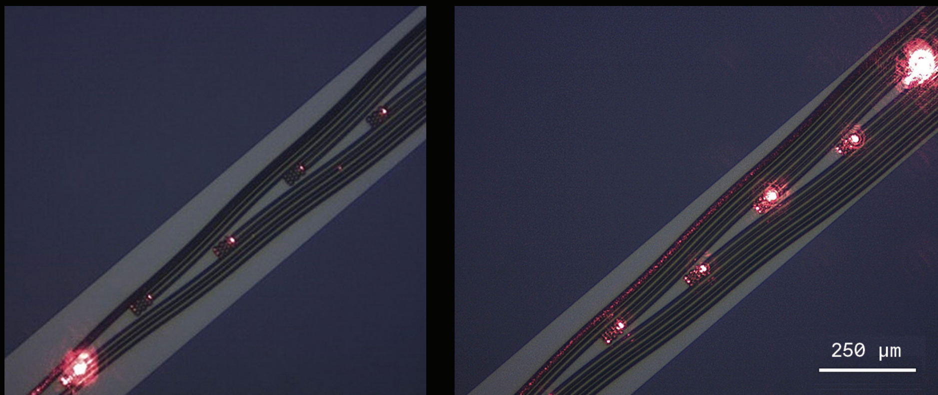
However, the use of CatCh has two problems: First, it requires blue light, which is associated with phototoxicity. When light, particularly high-energy blue light, shines directly on cells that are typically in the dark of the body's interior, these cells can be damaged and eventually die off. The other problem with CatCh is that it's slow to reset. At body temperature, once CatCh is activated by light, it takes about a dozen milliseconds to close the channel and be ready for the next activation. Such slow kinetics do not support the precise timing of neuron activation necessary to encode sound, which can require more than a hundred spikes per second. Many people said the kinetics of channelrhodopsins made our quest impossible—that even if we gained spectral resolution, we'd lose temporal resolution. But we took those doubts as a strong motivation to look for faster channelrhodopsins, and ones that respond to red light.

We are proposing a new type of implanted medical device that will be paired with a new type of gene therapy.

We were excited when a leader in optogenetics, Edward Boyden at MIT, discovered a faster-acting channelrhodopsin that his team called Chronos. Although it still required blue light for activation, Chronos was the fastest channelrhodopsin to date, taking about 3.6 milliseconds to close at room temperature. Even better, we found that it closed within about 1 ms at the warmer temperature of the body. However, it took some extra tricks to get Chronos working in the cochlea: We had to use powerful viral vectors and certain genetic sequences to improve the delivery of Chronos protein to the cell membrane of the cochlear neurons. With those tricks, both single neurons and the neural population responded robustly and with good temporal precision to optical stimulation at higher rates of up to about 250 Hz. So Chronos enabled us to elicit near-natural rates of neural firing, suggesting that we could have both frequency and time resolution. But we still needed to find an ultrafast channelrhodopsin that operated with longer wavelength light.

We teamed up with Bamberg to take on the challenge. The collaboration targeted Chrimson, a channelrhodopsin first described by Boyden that's best stimulated by orange light. The first results of our engineering experiments with Chrimson were fast Chrimson (f-Chrimson) and very fast Chrimson (vf-Chrimson). We were pleased to discover that f-Chrimson enables cochlear neurons to respond to red light reliably up to stimulation rates of approximately 200 Hz. Vf-Chrimson is even faster but is less well expressed in the cells than f-Chrimson is; so far, vf-Chrimson has not shown a measurable advantage over f-Chrimson when it comes to high-frequency stimulation of cochlear neurons.

We've also been exploring our options for the implanted light source that will trigger the optogenetic cells. The implant must be small enough to fit into the limited space of the cochlea, stiff enough for surgical insertion, yet flexible enough to gently follow the cochlea's curvature. Its housing must be biocompatible, transparent, and robust enough to last for decades. My collaborators Ulrich Schwarz and Patrick Ruther, then at the University of Freiburg, started things off by developing the first micro-light-emitting diodes (microLEDs) for optical cochlear implants.



Another design possibility for optical cochlear implants is to use laser diodes as a light source and pair them with optical fibers made of a flexible polymer. The laser diode could be safely encapsulated outside the cochlea, which would reduce concerns about heat, while polymer waveguide arrays [left and right images] would curl into the cochlea to deliver the light to the cells.

We found microLEDs useful because they're a very mature commercial technology with good power efficiency. We conducted several experiments with microfabricated thin-film microLEDs and demonstrated that we could optogenetically stimulate the cochlear nerve in our targeted frequency ranges. But microLEDs have drawbacks. For one thing, it's difficult to establish a flexible, transparent, and durable hermetic seal around the implanted microLEDs. Also, microLEDs with the highest efficiency emit blue light, which brings us back to the phototoxicity problem. That's why we're also looking at another way forward.

Instead of getting the semiconductor emitter itself into the cochlea, the alternative approach puts the light source, such as a laser diode, farther away in a hermetically sealed titanium housing. Optical fibers then bring the light into the cochlea and to the light-sensitive neurons. The optical fibers must be biocompatible, durable, and flexible enough to wind through the cochlea, which may be challenging with typical glass fibers. There's interesting ongoing research in flexible polymer fibers, which might have better mechanical characteristics, but so far, they haven't matched glass in efficiency of light propagation. The fiber-optic approach could have efficiency drawbacks, because we'd lose some light when it goes from the laser diode to the fiber, when it travels down the fiber, and when it goes from the fiber to the cochlea. But the approach seems promising, as it ensures that the optoelectronic components could be safely sealed up and would likely make for an easy insertion of the flexible waveguide array.

In the 2030s, people all over the world could begin to hear the light.

As we consider assembling these components into a commercial medical device, we first look for parts of existing cochlear implants that we can adopt. The audio processors that work with today's cochlear implants can be adapted to our purpose; we'll just need to split up the signal into more channels with smaller frequency ranges. The external transmitter and implanted receiver also could be similar to existing technologies, which will make our regulatory pathway that much easier. But the truly novel parts of our system—the optical stimulator and the gene therapy to deliver the channelrhodopsins to the cochlea—will require a good amount of scrutiny.

Cochlear implant surgery is quite mature and typically takes only a couple of hours at most. To keep things simple, we want to keep our procedure as close as possible to existing surgeries. But the key part of the surgery will be quite different: Instead of inserting electrodes into the cochlea, surgeons will first administer viral vectors to deliver the genes for the channelrhodopsin to the cochlear nerve cells, and then implant the light emitter into the cochlea.

Since researchers are just beginning to test optogenetic therapies in clinical trials, there's still some uncertainty about how best to make the technique work in humans. We're still thinking about how to get the viral vector to deliver the necessary genes to the correct neurons in the cochlea. The viral vector we've used in experiments thus far, an adeno-associated virus, is a harmless virus that has already been approved for use in several gene therapies, and we're using some genetic tricks and local administration to target cochlear neurons specifically.

We've already begun gathering data about the stability of the optogenetically altered cells and whether they'll need repeated injections of the channelrhodopsin genes to stay responsive to light.

Our road map to clinical trials is very ambitious. We're working now to finalize and freeze the design of the device, and we have ongoing preclinical studies in animals to check for phototoxicity and prove the efficacy of the basic idea. We aim to begin our first-in-human study in 2026, in which we'll find the safest dose for the gene therapy. We hope to launch a large phase 3 clinical trial in 2028 to collect data that we'll use in submitting the device for regulatory approval, which we could win in the early 2030s.

We foresee a future in which beams of light can bring rich soundscapes to people with profound hearing loss or deafness. We hope that the optical cochlear implant will enable them to pick out voices in a busy meeting, appreciate the subtleties of their favorite songs, and take in the full spectrum of sound—from trilling birdsongs to booming bass notes. We think this technology has the potential to illuminate their auditory worlds. ■

Will AI Steal Submarines' Stealth?

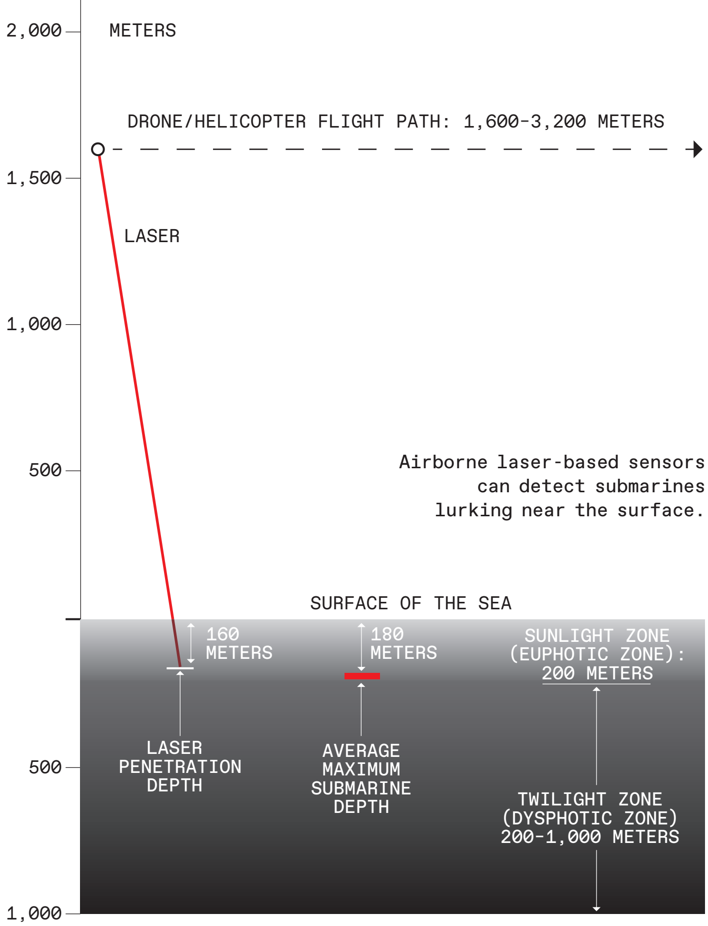
Better detection will make the oceans transparent—and perhaps undermine nuclear deterrence

By Natasha Bajema

SUBMARINES ARE VALUED PRIMARILY FOR THEIR ABILITY TO HIDE. The assurance that submarines would likely survive the first missile strike in a nuclear war and thus be able to respond by launching missiles in a second strike is key to the strategy of deterrence known as mutually assured destruction. Any new technology that might render the oceans effectively transparent, making it trivial to spot lurking submarines, could thus undermine the peace of the world. For nearly a century, naval engineers have striven to develop ever-faster, ever-quieter submarines. But they have worked just as hard at advancing a wide array of radar, sonar, and other technologies designed to detect, target, and eliminate enemy submarines. • The balance seemed to turn with the emergence of nuclear-powered submarines in the early 1960s. In a 2015 study for the Center for Strategic and Budgetary Assessment, Bryan Clark, a naval specialist now at the Hudson Institute, noted that the ability of these boats to remain submerged for long periods of time made them "nearly impossible to find with radar and active sonar." But even these stealthy submarines produce subtle, very-low-frequency noises that can be picked up from far away by networks of acoustic hydrophone arrays mounted to the seafloor. • And now the game of submarine hide-and-seek may be approaching the point at which submarines can no longer elude detection and simply disappear.

It may come as early as 2050, according to a recent study by the National Security College of the Australian National University, in Canberra. This timing is particularly significant because the enormous costs required to design and build a submarine are meant to be spread out over at least 60 years. A submarine that goes into service today should still be in service in 2082. Nuclear-powered submarines, such as the Virginia-class fast-attack submarine, each cost roughly US $2.8 billion, according to the U.S. Congressional Budget Office. And that's just the purchase price; the total life cycle cost for the new Columbia-class ballistic-missile submarine is estimated to exceed $395 billion.

The twin problems of detecting submarines of rival countries and protecting one's own submarines from detection are enormous, and the technical details are closely guarded secrets. Many naval experts are speculating about sensing technologies that could be used in concert with modern AI methodologies to neutralize a submarine's stealth. Rose Gottemoeller, former deputy secretary general of NATO, warns that "the stealth of submarines will be difficult to sustain, as sensing of all kinds, in multiple spectra, in and out of the water becomes more ubiquitous." And the ongoing contest between stealth and detection is becoming increasingly volatile as these new technologies threaten to overturn the balance.



T**oday's sensing technologies** for detecting submarines are moving beyond merely hearing submarines to pinpointing their position through a variety of nonacoustic techniques. Submarines can now be detected by the tiny amounts of radiation and chemicals they emit, by slight disturbances in the Earth's magnetic fields, and by reflected light from laser or LED pulses. All these methods seek to detect anomalies in the natural environment, as represented in sophisticated models of baseline conditions that have been developed within the last decade, thanks in part to Moore's Law advances in computing power.

According to experts at the Center for Strategic and International Studies, in Washington, D.C., two methods offer particular promise. Lidar sensors transmit laser pulses through the water to produce highly accurate 3D scans of objects. Magnetic anomaly detection (MAD) instruments monitor the Earth's magnetic fields and can detect subtle disturbances caused by the metal hull of a submerged submarine.

Both sensors have drawbacks. MAD works only at low altitudes or underwater. It is often not sensitive enough to pick out the disturbances caused by submarines from among the many other subtle shifts in electromagnetic fields under the ocean.

Lidar has better range and resolution and can be installed on satellites, but it consumes a lot of power—a standard automotive unit with a range of several hundred meters can burn 25 watts. Lidar is also prohibitively expensive, especially when operated in space. In 2018, NASA launched a satellite with laser imaging technology to monitor changes in Earth's surface—notably changes in the patterns on the ocean's surface; the satellite cost more than $1 billion.

Indeed, where you place the sensors is crucial. Underwater sensor arrays won't put an end to submarine stealth by themselves. Retired Rear Adm. John Gower, former submarine commander for the Royal Navy of the United Kingdom, notes that sensors "need to be placed somewhere free from being trolled or fished, free from seismic activity, and close to locations from which they can be monitored and to which they can transmit collected data. That severely limits the options available."

One way to get around the need for precise placement is to make the sensors mobile. Underwater drone swarms can do just that, which is why some experts have proposed them as the ultimate antisubmarine capability.

Clark, for instance, notes that such drones now have enhanced computing power and batteries that can last for two weeks between charges. The U.S. Navy is working on a drone that could run for 90 days. Drones are also now equipped with the chemical, optical, and geomagnetic sensors mentioned earlier. Networked underwater drones, perhaps working in conjunction with airborne drones, may be useful for not only detecting submarines but also destroying them, which is why several militaries are investing heavily in them.

For example, the Chinese Navy has invested in a fishlike undersea drone known as Robo-Shark, which was designed specifically for hunting submarines. Meanwhile, the U.S. Navy is developing the Low-Cost Unmanned Aerial Vehicle Swarm-

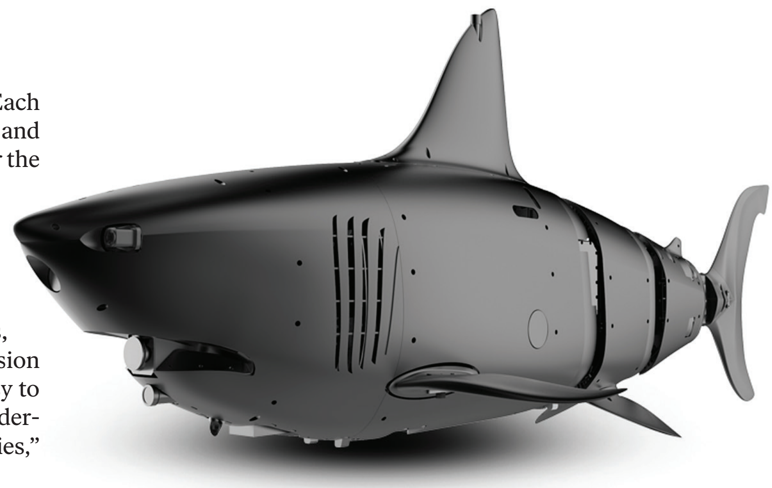
A U.S. Navy Poseidon P-8 aircraft, equipped to detect submarines, awaits refueling in Okinawa, Japan, in 2020.

ing Technology, for conducting surveillance missions. Each Locust drone weighs about 6 kilograms, costs $15,000, and can be outfitted with MAD sensors; it can skim low over the ocean's surface to detect signals under the water. Militaries study the drone option because it might work. Then again, it very well might not.

Gower considers underwater drones to be "the least likely innovation to make a difference in the decline of submarine stealth." A navy would need a lot of drones, data rates are exceedingly slow, and a drone's transmission range is short. Drones are also noisy and extremely easy to detect. "Not to mention that controlling thousands of underwater drones far exceeds current technological capabilities," he adds.

Gower says it could be possible "to use drones and sonar networks together in choke points to detect submarine patrols." Among the strategically important submarine patrol choke points are the exit routes on either side of Ireland, for U.K. submarines; those around the islands of Hainan and Taiwan, for Chinese submarines; in the Barents or Kuril Island chain, for Russian submarines; and the Straits of Juan de Fuca, for U.S. Pacific submarines. On the other hand, he notes, "They could be monitored and removed since they would be close to sovereign territories. As such, the challenges would likely outweigh the gains."

Gower believes a more powerful means of submarine detection lies in the "persistent coverage of the Earth's surface by commercial satellites," which he says "represents the most substantial shift in our detection capabilities compared to the past." More than 2,800 of these satellites are already in orbit. Governments once dominated space because the cost of building and launching satellites was so great. These days, much cheaper satellite technology is available, and private companies are launching constellations of tens to thousands of satellites that can work together to image every bit of the Earth's surface. They are outfitted with a wide range of sensing technologies, including synthetic aperture radar (SAR), which scans a scene down below while moving over a great distance, providing results like those you'd get from an extremely long antenna. Since these satellite constellations view the same locations multiple times per day, they can capture small changes in activity.



Robo-Shark, a 2.2-meter-long submersible made by Boya Gongdao Robot Technology, of Beijing, is said to be capable of underwater surveillance and unspecified antisubmarine operations. The company says that the robot moves at up to 5 meters per second (10 knots) by using a three-joint structure to wave the tail fin, making less noise than a standard propeller would.

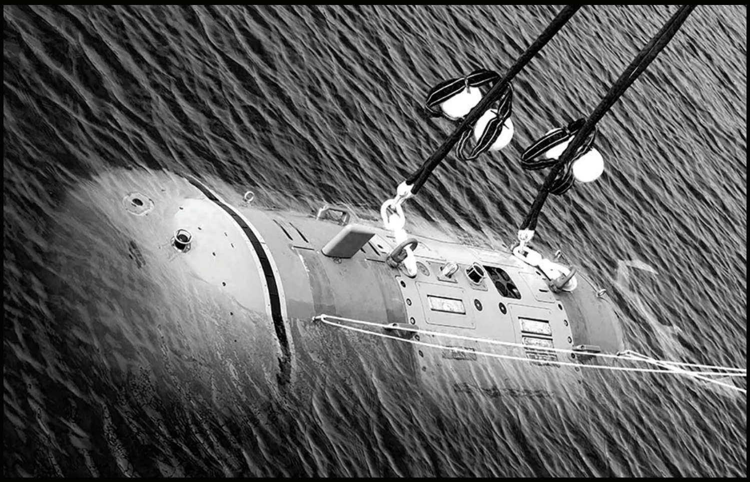
TOP: U.S. NAVY; BOTTOM: ROBOSEA.ORG

Experts have known for decades about the possibility of detecting submarines with SAR based on the wake patterns they form as they move through the ocean. To detect such patterns, known as Bernoulli humps and Kelvin wakes, the U.S. Navy has invested in the AN/APS-154 Advanced Airborne Sensor, developed by Raytheon. The aircraft-mounted radar is designed to operate at low altitudes and appears to be equipped with high-resolution SAR and lidar sensors.

Commercial satellites equipped with SAR and other imaging instruments are now reaching resolutions that can compete with those of government satellites and offer access to customers at extremely affordable rates. In other words, there's lots of relevant, unclassified data available for tracking submarines, and the volume is growing exponentially.

One day this trend will matter. But not just yet.

Jeffrey Lewis, director of the East Asia Nonproliferation



A Northrop Grumman MQ-8C [left], an uncrewed helicopter, has recently been deployed by the U.S. Navy in the Indo-Pacific area for use in surveillance. In the future, it will also be used for antisubmarine operations. The Boeing Orca [top right], the largest underwater drone in the U.S. Navy's inventory, was christened in April, in Huntington Beach, Calif. The craft is designed for, among other things, use in antisubmarine warfare. A Snakehead [bottom right], a large underwater drone designed to be launched and recovered by U.S. Navy nuclear-powered submarines, is shown at its launching ceremony in Narragansett Bay in Newport, R.I.

Program at the James Martin Center for Nonproliferation Studies, regularly uses satellite imagery in his work to track nuclear developments. But tracking submarines is a different matter. "Even though this is a commercially available technology, we still don't see submarines in real time today," Lewis says.

The day when commercial satellite imagery reduces the stealth of submarines may well come, says Gower, but "we're not there yet. Even if you locate a submarine in real time, 10 minutes later, it's very hard to find again."

Though these new sensing methods have the potential to make submarines more visible, no one of them can do the job on its own. What might make them work together is the master technology of our time: artificial intelligence.

"When we see today's potential of ubiquitous sensing capabilities combined with the power of big-data analysis," Gottemoeller says, "it's only natural to ask the question: Is it now finally possible?" She began her career in the 1970s, when the U.S. Navy was already worried about Soviet submarine-detection technology.

Unlike traditional software, which must be programmed in advance, the machine-learning strategy used here, called deep learning, can find patterns in data without outside help. Just this past year, DeepMind's AlphaFold program achieved a breakthrough in predicting how amino acids fold into proteins, making it possible for scientists to identify the structure of 98.5 percent of human proteins. Earlier work in games, notably Go and chess, showed that deep learning

CLOCKWISE FROM LEFT: NORTHROP GRUMMAN; BOEING; U.S. NAVY could outdo the best of the old software techniques, even when running on hardware that was no faster.

For AI to work in submarine detection, several technical challenges must be overcome. The first challenge is to train the algorithm, which involves acquiring massive volumes and varieties of sensor data from persistent satellite coverage of the ocean's surface as well as regular underwater collection in strategic locations. Using such data, the AI can establish a detailed model of baseline conditions, then feed new data into the model to find subtle anomalies. Such automated sleuthing is what's likeliest to detect the presence of a submarine anywhere in the ocean and predict locations based on past transit patterns.

The second challenge is collecting, transmitting, and processing the masses of data in real time. That task would require a lot more computing power than we now have, both in fixed and on mobile collection platforms. But even today's technology can start to put the various pieces of the technical puzzle together.

F**or some years to come,** the vastness of the ocean will continue to protect the stealth of submarines. But the very prospect of greater ocean transparency has implications for global security. Concealed submarines bearing ballistic missiles provide the threat of retaliation against a first nuclear strike. What if that changes?

"We take for granted the degree to which we rely upon having a significant portion of our forces exist in an essentially invulnerable position," Lewis says. Even if new developments did not reduce submarine stealth by much, the mere perception of such a reduction could undermine strategic stability.

Gottemoeller warns that "any perception that nuclear-armed submarines have become more targetable will lead to questions about the survivability of second-strike forces. Consequently, countries are going to do everything they can to counter any such vulnerability."

Experts disagree on the irreversibility of ocean transparency. Because any technological breakthroughs will not be implemented overnight, "nations should have ample time to develop countermeasures [that] cancel out any improved detection capabilities," says Matt Korda, senior research associate at the Federation of American Scientists, in Washington, D.C. However, Roger Bradbury and eight colleagues at the National Security College of the Australian National University disagree, claiming that any technical ability to counter detection technologies will start to decline by 2050.

Korda also points out that ocean transparency, to the extent that it occurs, "will not affect countries equally. And that raises some interesting questions." For example, U.S. nuclear-powered submarines are "the quietest on the planet. They are virtually undetectable. Even if submarines become more visible in general, this may have zero meaningful effect on U.S. submarines' survivability."

Sylvia Mishra, a new-tech nuclear officer at the European Leadership Network, a London-based think tank, says she is "more concerned about the overall problem of ambiguity under the sea." Until recently, she says, movement under the oceans was the purview of governments. Now, though, there's a growing industry presence under the sea. For example, companies are laying many underwater fiber-optic communication cables, Mishra says, "which may lead to greater congestion of underwater inspection vehicles, and the possibility for confusion."

Confusion might come from the fact that drones, unlike surface ships, do not bear a country flag, and therefore their ownership may be unclear. This uncertainty, coupled with the possibility that the drones could also carry lethal payloads, increases the risk that a naval force might view an innocuous commercial drone as hostile. "Any actions that hold the strategic assets of adversaries at risk may produce new touch points for conflict and exacerbate the risk of war," says Mishra.

Given the strategic importance of submarine stealth, Gower asks, "Why would any country want to detect and track submarines? It's only something you'd do if you want to make a nuclear-armed power nervous." Even in the Cold War, when the United States and the U.K. routinely tracked Soviet ballistic-missile submarines, they did so only because they knew their activities would go undetected—that is, without risking escalation. Gower postulates that this was dangerously arrogant: "To actively track second-strike nuclear forces is about as escalatory as you might imagine."

"All nuclear-armed states place a great value on their second-strike forces," Gottemoeller says. If greater ocean transparency produces new risks to their survivability, real or perceived, she says, countries may respond in two ways: build up their nuclear forces further and take new measures to protect and defend them, producing a new arms race; or else keep the number of nuclear weapons limited and find other ways to bolster their viability.

Ultimately, such considerations have not dampened the enthusiasm of certain governments for acquiring submarines. In September 2021 the Australian government announced an enhanced trilateral partnership with the United States and the United Kingdom. The new deal, known as AUKUS, will provide Australia with up to eight nuclear-powered submarines with the most coveted propulsion technology in the world. However, it could be at least 20 years before the Royal Australian Navy can deploy the first of its new subs.

As part of its plans for nuclear modernization, the United States has started replacing its entire fleet of 14 Ohio-class ballistic-missile submarines with new Columbia-class boats. The replacement program is projected to cost more than $128 billion for acquisition and $267 billion over their full life cycles. U.S. government officials and experts justify the steep cost of these submarines with their critical role in bolstering nuclear deterrence through their perceived invulnerability.

To protect the stealth of submarines, Mishra says, "There is a need for creative thinking. One possibility is exploring a code of conduct for the employment of emerging technologies for surveillance missions."

There are precedents for such cooperation. During the Cold War, the United States and the Soviet Union set up a secure communications system—a hotline—to help prevent a misunderstanding from snowballing into a disaster. The two countries also developed a body of rules and procedures, such as never to launch a missile along a potentially threatening trajectory. Nuclear powers could agree to exercise similar restraint in the detection of submarines. The stealthy submarine isn't gone; it still has years of life left. That gives us ample time to find new ways to keep the peace. ■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The Spectacular COLLAPSE of CRYPTOKITTIES

What the first big blockchain game says about NFTs and the future of cryptocurrency

Illustration by Frank Stockton

BY MATTHEW S. SMITH

ON 4 SEPTEMBER 2018, someone known only as Rabono bought an angry cartoon cat named Dragon for 600 ethers—an amount of Ethereum cryptocurrency worth about US $170,000 at the time, or $745,000 at the cryptocurrency's value in July 2022. ● It was by far the highest-priced transaction yet for a nonfungible token (NFT), the then-new concept of a unique digital asset. And it was a headline-grabbing opportunity for *CryptoKitties*, the world's first blockchain gaming hit. But the sky-high cost of the transaction obscured a more difficult truth: *CryptoKitties* was dying, and it had been for some time. ● Dragon was never resold—a strange fate for one of the most historically relevant NFTs ever. Newer NFTs such as "The Merge," a piece of digital art that sold for the equivalent of $92 million, left Dragon behind as the NFT market surged to record sales, totaling roughly $18 billion in 2021. Has the world simply moved on to newer blockchain projects? Or is this the fate that awaits all NFTs?

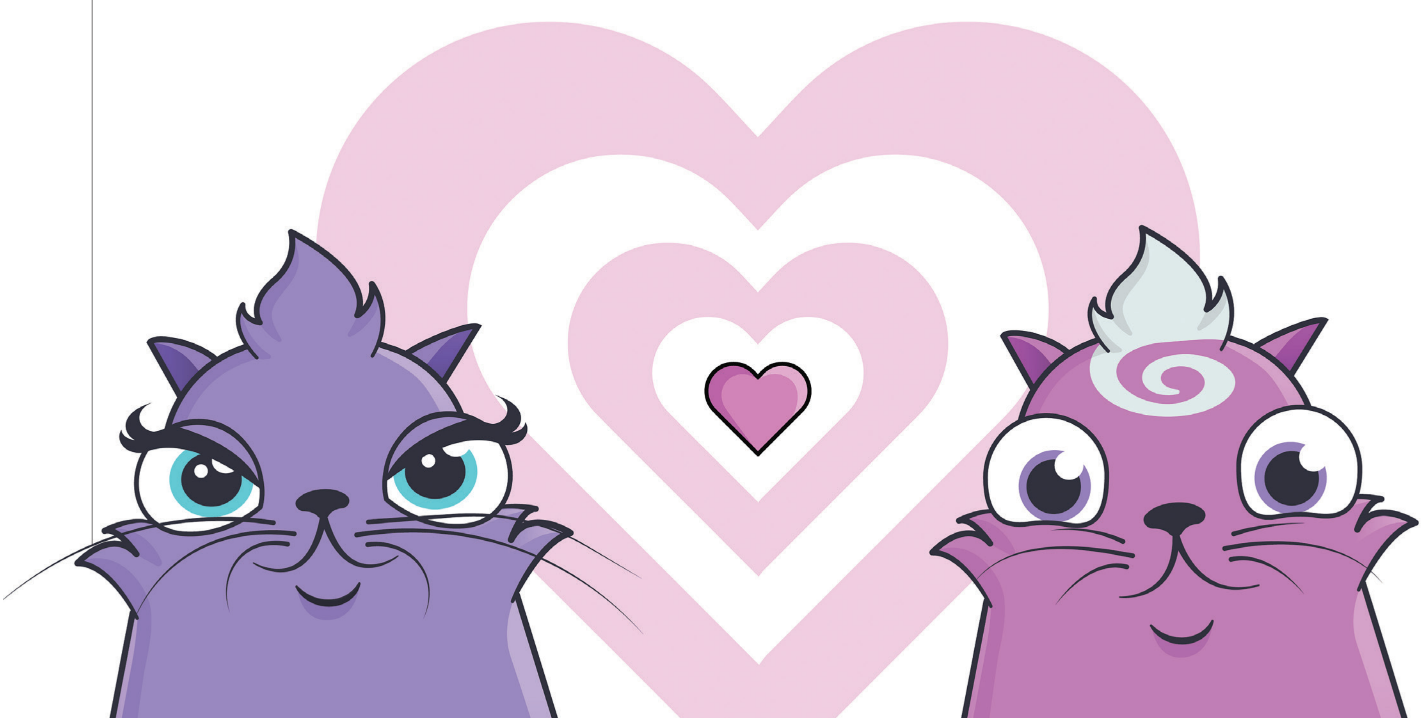
BLOCKCHAINS, SMART CONTRACTS, AND CAT GENES

TO UNDERSTAND the slow death of *CryptoKitties*, you have to start at the beginning. Blockchain technology arguably began with a 1982 paper by the computer scientist David Chaum, but it reached mainstream attention with the success of Bitcoin, a cryptocurrency created by the anonymous person or persons known as Satoshi Nakamoto. At its core, a blockchain is a simple ledger of transactions placed one after another—not unlike a very long Excel spreadsheet.

The complexity comes in how blockchains keep the ledger stable and secure without a central authority; the details of how that's done vary among blockchains. Bitcoin, though popular as an asset and useful for moneylike transactions, has limited support for doing anything else. Newer alternatives, such as Ethereum, gained popularity because they allow for complex "smart contracts"—executable code stored in the blockchain.

CryptoKitties was among the first projects to harness smart contracts by attaching code to data constructs called tokens, on the Ethereum blockchain. Each chunk of the game's code (which it refers to as a "gene") describes the attributes of a digital cat. Players buy, collect, sell, and even breed new felines. Just like individual Ethereum tokens and bitcoins, the cat's code also ensures that the token representing each cat is unique, which is where the nonfungible token, or NFT, comes in. A fungible good is, by definition, one that can be replaced by an identical item—one bitcoin is as good as any other bitcoin. An NFT, by contrast, has unique code that applies to no other NFT.

There's one final piece of the blockchain puzzle you need to understand: "gas." Some blockchains, including Ethereum, charge a fee for the computational work the network must do to verify a transaction. This creates an obstacle to overworking the



ALL ILLUSTRATIONS: DAPPER LABS

What's a CryptoKitty?

Each CryptoKitty is a token, a set of data on the Ethereum blockchain. Unlike the cryptocurrencies Ethereum and Bitcoin, these tokens are nonfungible—that is, they are not interchangeable.

Unique ID	Mother's ID, father's ID	Genes
The unique ID makes a CryptoKitty a nonfungible token.	The token contains the kitty's lineage and other data.	The kitty's genes determine its unique look.

blockchain's network. High demand means high fees, encouraging users to think twice before making a transaction. The resulting reduction in demand protects the network from being overloaded and transaction times from becoming excessively long. But it can be a weakness when an NFT game goes viral.

THE RISE AND FALL OF CRYPTOKITTIES

LAUNCHED ON 28 NOVEMBER 2017 after a five-day closed beta, *CryptoKitties* skyrocketed in popularity on an alluring tagline: the world's first Ethereum game.

"As soon as it launched, it pretty much immediately went viral," says Bryce Bladon, a founding member of the team that created *CryptoKitties*. "That was an incredibly bewildering time."

Sales volume surged from just 1,500 nonfungible felines on launch day to more than 52,000 on 10 December 2017, according to NonFungible.com, with many CryptoKitties selling for valuations in the hundreds or thousands of dollars. The value of the game's algorithmically generated cats led to coverage in hundreds of publications.

What's more, the game arguably drove the success of Ethereum, the blockchain used by the game. Ethereum took off like a rocket in tandem with the release of *CryptoKitties*, climbing from just under $300 per token at the beginning of November 2017 to just over $1,360 in January 2018.

Ethereum's rise continued with the launch of dozens of new blockchain games based on the cryptocurrency through late 2017 and 2018. *Ethermon*, *Ethercraft*, *Ether Goo*, *CryptoCountries*, *CryptoCelebrities*, and *CryptoCities* are among the better-known examples. Some arrived within weeks of *CryptoKitties*.

This was the break fans of Ethereum were waiting for. Yet, in what would prove an ominous sign for the health of blockchain gaming, *CryptoKitties* stumbled as Ethereum dashed higher.

Daily sales peaked in early December 2017, then slid into January and, by March, averaged less than 3,000. The value of the NFTs themselves declined more slowly, a sign the game had a base of dedicated fans like Rabono, who bought Dragon well after the game's peak. Their activity set records for the value of NFTs through 2018. This kept the game in the news but failed to lure new players.

Today, *CryptoKitties* is lucky to break 100 sales a day, and the total value is often less than $10,000. Large transactions, like the sale of Founder Cat #71 for 60 ethers (roughly $170,000) on 30 April 2022, do still occur—but only once every few months. Most nonfungible fur-babies sell for tiny fractions of 1 ether, worth just tens of dollars in July 2022.

CryptoKitties' plunge into obscurity is unlikely to reverse. Dapper Labs, which owns *CryptoKitties*, has moved on to projects such as NBA Top Shot, a platform that lets basketball fans purchase NFT "moments"—essentially video clips—from NBA games. Dapper Labs did not respond to requests for an interview about *CryptoKitties*. Bladon left Dapper in 2019.

WHAT WENT WRONG?

ONE CLUE TO THE GAME'S DEMISE can be found in the last post on the game's blog (4 June 2021), which celebrates the breeding of the 2 millionth CryptoKitty. Breeding, a core mechanic of the game, lets owners pair their existing NFTs to create algorithmically generated offspring. This gave the NFTs inherent value in the game's ecosystem. Each NFT was able to generate more NFTs, which players could then resell for profit. But this game mechanism also saturated the market. Xiaofan Liu, an assistant professor in the department of media and communication at City University of Hong Kong who coauthored a paper on *CryptoKitties*' rise and fall, sees this as a flaw the game could never overcome.

"The price of a kitty depends first on rarity, and that depends on the gene side. And the second dimension is just how many kitties are on the market," Liu says. "With more people came more kitties."

More players meant more demand, but it also meant more opportunities to create supply through breeding new cats. This quickly diluted the rarity of each NFT.

Bladon agrees with that assessment of the breeding mechanism. "I think the criticism is valid," he says, explaining that it was meant to provide a sense of discovery and excitement. He also hoped it would encourage players to hold on to NFTs instead of immediately selling, as breeding, in theory, provided lasting value.

The sheer volume of CryptoKitties caused another, more immediate problem: It functionally broke the Ethereum blockchain, which is the world's second most valuable cryptocurrency by market capitalization (after Bitcoin). As explained earlier, Ethereum uses a fee called gas to price the cost of transactions. Any spike in transactions—buying, siring, and so on—will cause a spike in gas fees, and that's exactly what happened when *CryptoKitties* went to the moon.

"Players who wanted to buy CryptoKitties incurred high gas fees," Mihai Vicol, market analyst at Newzoo, said in an interview. "Those gas fees were anywhere from $100 to $200 per transaction. You had to pay the price of the CryptoKitty, plus the gas fee. That's a major issue."

The high fees weren't just a problem for *CryptoKitties*. It was an issue for the entire blockchain. Anyone who wanted to trans-

The Game

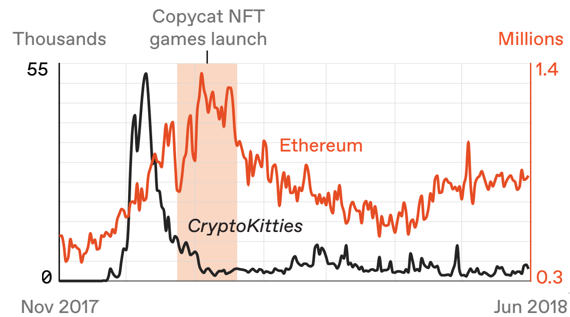
The *CryptoKitties* blockchain game involves collecting, selling, and breeding nonfungible felines. The example here assumes your kitty is female.

act in Ethereum, for any reason, had to pay more for gas as the game became more successful.

This dynamic remains a problem for Ethereum today. On 30 April 2022, when Yuga Labs released Otherdeeds—NFTs that promise owners metaverse real estate—it launched Ethereum gas fees into the stratosphere. The average price of gas briefly exceeded the equivalent of $450, up from about $50 the day before.

Although *CryptoKitties*' demands on the network subsided as players left, gas will likely be the final nail in the game's coffin. The median price of a CryptoKitty in the past three months is about 0.04 ethers, or $40 to $50, which is often less than the gas required to complete the transaction. Even those who want to casually own and breed inexpensive CryptoKitties for fun can't do it without spending hundreds of dollars.

Daily Transaction Volume



The launch of *CryptoKitties* drove up the number of transactions on the Ethereum blockchain. Even as the game's daily transaction volume plummeted, the number of Ethereum transactions continued to rise, possibly because of the arrival of multiple copycat NFT games.

BLOCKCHAIN GAMES: TWO STEPS FORWARD, ONE STEP BACK

THE RISE AND FALL of *CryptoKitties* was dramatic but gave its successors—of which there are hundreds—a chance to learn from its mistakes and move past them. Many have failed to heed the lessons: Modern blockchain gaming hits such as *Axie Infinity* and *BinaryX* had a similar initial surge in price and activity followed by a long downward spiral.

"Anything that was emblematic of *CryptoKitties*' success was aped. Anything that wasn't immediately visible was mostly ignored," says Bladon. And it turns out many of *CryptoKitties*' difficulties weren't visible to the public. "The thing is, the *CryptoKitties* project did stumble. We had a lot of outages. We had to deal with a lot of people who'd never used blockchain before. We had a bug that leaked tens of thousands of dollars of ether." Similar problems have plagued more recent NFT projects, often on a much larger scale.

Liu isn't sure how blockchain games can curb this problem. "The short answer is, I don't know," he says. "The long answer is, it's not just a problem of blockchain games."

World of Warcraft, for example, has faced rampant inflation for most of the game's life. This is caused by a constant influx of gold from players and the ever-increasing value of new items introduced by expansions. The continual need for new players and items is linked to another core problem of today's blockchain games: They're often too simple.

"I think the biggest problem blockchain games have right now is they're not fun, and if they're not fun, people don't want to invest in the game itself," says Newzoo's Vicol. "Everyone who spends money wants to leave the game with more money than they spent."

That perhaps unrealistic wish becomes impossible once the downward spiral begins. Players, feeling no other attachment to the game than growing an investment, quickly flee and don't return.

Whereas some blockchain games have seemingly ignored the perils of *CryptoKitties*' quick growth and long decline, others have learned from the strain it placed on the Ethereum network. Most blockchain games now use a sidechain, a blockchain that exists independently but connects to another, more prominent "parent" blockchain. The chains are connected by a bridge that facilitates the transfer of tokens between each chain. This prevents a rise in fees on the primary blockchain, as all game activity occurs on the sidechain.

Yet even this new strategy comes with problems, because sidechains are proving to be less secure than the parent blockchain. An attack on Ronin, the sidechain used by *Axie Infinity*, let the hackers get away with the equivalent of $600 million. Polygon, another sidechain often used by blockchain games, had to patch an exploit that put $850 million at risk and pay a bug bounty of $2 million to the hacker who spotted the issue. Players who own NFTs on a sidechain are now warily eyeing its security.

REMEMBER DRAGON

THE CRYPTOCURRENCY WALLET that owns the near-million-dollar kitten Dragon now holds barely 30 dollars' worth of ether and hasn't traded in NFTs for years. Wallets are anonymous, so it's possible the person behind the wallet moved on to another. Still, it's hard not to see the wallet's inactivity as a sign that, for Rabono, the fun didn't last.

Whether blockchain games and NFTs shoot to the moon or fall to zero, Bladon remains proud of what *CryptoKitties* accomplished and hopeful it nudged the blockchain industry in a more approachable direction.

"Before *CryptoKitties*, if you were to say 'blockchain,' everyone would have assumed you're talking about cryptocurrency," says Bladon. "What I'm proudest of is that it was something genuinely novel. There was real technical innovation, and seemingly, a real culture impact." ■

Inside the Universe Machine

CONTINUED FROM PAGE 29

information concerning the telescope's day-to-day activities.

Any scientific data JWST collects during its lifetime will need to be stored on board, because the spacecraft doesn't maintain round-the-clock contact with Earth. Data gathered from its scientific instruments is stored within the spacecraft's 68-GB solid-state drive (3 percent is reserved for engineering and telemetry data). Alex Hunter, also a flight-systems engineer at the Space Telescope Science Institute, says that by the end of JWST's 10-year mission, they expect to be down to about 60 GB because of deep-space radiation and wear and tear.

The onboard storage is enough to collect data for about 24 hours before it runs out of room. Well before that becomes an issue, JWST will have opportunities to beam that data to Earth.

JWST will stay connected via the Deep Space Network (DSN)—a resource it shares with the Parker Solar Probe, the Transiting Exoplanet Survey Satellite, the Voyager probes, and the entire ensemble of Mars rovers and orbiters, to name just a few of the other heavyweights. The DSN consists of three antenna complexes: in Canberra, Australia; Madrid, Spain; and Barstow, Calif.

Sandy Kwan, a DSN systems engineer, says that contact windows with spacecraft are scheduled 12 to 20 weeks in advance. JWST had a greater number of scheduled contact windows during its commissioning phase, as instruments were brought on line, checked, and calibrated. Most of that process required real-time communication with Earth.

All of the communications channels use the Reed-Solomon error-correction protocol—the same error-correction standard used in DVDs and Blu-ray discs as well as QR codes. The lower-data-rate S-band channels use binary phase-shift keying—involving phase shifting of a signal's carrier wave. The K-band channel, however, uses a quadrature phase-shift keying. Quadrature phase-shift keying can double a channel's data rate, at the cost of more complicated transmitters and receivers.

JWST's communications with Earth incorporate an acknowledgment protocol—only after JWST gets confirmation that a file has been successfully received will it delete its copy.

The communications system was assembled along with the rest of the spacecraft bus by Northrop Grumman, using off-the-shelf components sourced from multiple manufacturers.

JWST has had a long and often-delayed development, but its communications system has always been a bedrock for the rest of the project. Keeping the system dependable means it's one less thing to worry about. Menzel can remember, for instance, ideas for laser-based optical systems that were invariably rejected. "I can count at least two times where I had been approached by people who wanted to experiment with optical communications," says Menzel. "Each time they came to me, I sent them away with the old 'Thank you, but I don't need it. And I don't want it.'" —MICHAEL KOZIOL

THE INSTITUTE

NEWS OF THE IEEE
VOLUME 46 / ISSUE 3

LA TROBE UNIVERSITY

Eddie Custovic Builds Tech to End Famine P. 52

A Promise Is a Promise

MY GREAT-GRANDFATHER WAS the kindest man I ever met. A self-taught accountant without formal education, he lived in the impoverished countryside of southern Taiwan. Legend has it that because members of the community viewed him as trustworthy, humble, and hardworking, they hired him to do their bookkeeping. He escaped a future of being a struggling farmer and was able to build a successful business.

He was also a vegetarian. While there were many special occasions and festivals in his sleepy village where meat was served, he always chose to eat his simple vegetarian meals away from others. I always wondered why. I came to learn that it was because my great-grandfather made a promise to Buddha.

Many years ago, my grandfather was a medical student studying in Japan. After a vacation home to Taiwan with my grandmother, they returned to Japan by boat, during which time he became very ill. World War II was raging, and medical supplies were limited. Unfortunately, by the time the necessary supplies reached my grandfather, it was too late.

Later, my great-uncle went to Japan to study medicine and he also became quite sick. That was when my great-grandfather made a promise to Buddha: If you let my second son live, I will forever be a vegetarian to honor you. My great-uncle survived.

My great-grandfather's wish came true, and until he passed away in his 90s, he never broke his promise, a simple vow between him and Buddha. A promise is a promise.

I strongly believe that integrity is the essence of everything successful, and character is what you do when no one is watching. Ethics serves as my ultimate guide for how I conduct myself both personally and professionally.

Because we are in a profession that often deals with innovation and safety, all members of our community—engineers, technologists, scientists, practitioners, and entrepreneurs—should have the highest ethical standards.

IEEE has recently revised its Code of Ethics, which encourages our members to strive to comply with ethical design and sustainable development practices. This is crucial given the global scale of the environmental, social, and political challenges that threaten to rapidly and critically impact the living conditions of current and future generations.

Fair opportunity for participation

At the time of my grandfather's death, my grandmother was pregnant with my mother. Because of this, she dropped out of medical school. During this era, a widow was expected to remain as such, even though my grandmother was only in her twenties. She chose to get remarried, an act that was unforgivable then. Thus, my mother was raised by my great-grandfather.

My grandmother was ahead of her time and dared to defy tradition. She was an outstanding athlete and an excellent student, with both ambition and potential. However, she lived during an era when women seldom received an education, not to mention the opportunity to attend medical school.

In the end, tradition won. After remarrying, she had more children and became a housewife, not a doctor as she had planned. How many women in the world still face such obstacles?

Making progress in engineering, technology, and science is a global endeavor with worldwide implications. This progress is guided best by having an open, diverse, and inclusive mindset with the goal of developing and sharing innovative solutions for the benefit of all.

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IEEE

Throughout my lifelong relationship with IEEE—my professional home—what I have treasured most is having the opportunity to befriend colleagues from around the world, from different cultures, with different beliefs, ways of life, and languages. My work, with IEEE and professionally, has taken me to several continents to collaborate and work with others. Through this global network I have been able to learn from the best and brightest minds in the world, and have come to greatly appreciate the diversity of cultures of IEEE members. Everyone has their own unique wisdom to offer.

IEEE continues its efforts to strengthen diversity and inclusivity across the organization and in the broader technological community.

The establishment of the IEEE Diversity and Inclusion Committee as a standing committee of the IEEE Board of Directors follows the organization's long-standing commitment to maintaining an environment in which all are welcome to collaborate and contribute to the community, to support the growth of the profession and colleagues, and to advance technology for the benefit of humanity.

Additionally, IEEE has devoted considerable effort in the past few years revising policies, procedures, and bylaws to ensure that members have a safe, inclusive place where all feel welcome.

These activities help ensure all our members have full access to the benefits of membership, including opportunities for professional development and recognition.

As president, I made a commitment to help shape the IEEE of the future by examining ways in which the organization can evolve to best meet the needs of all technical professionals.

I also made a promise to every member from all of our diverse groups and regions, especially women and others from underrepresented communities, that they will have a fair opportunity for participation and leadership in our professional home.

And a promise is a promise.

—K.J. RAY LIU
IEEE president and CEO

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

EDITOR'S NOTE

Honoring the Work of Exceptional Innovators

They invented denser chips, digital cameras, and more

THE ENGINEERS WHO receive IEEE's top awards have changed the world for the better.

Consider the award recipients featured in this issue. Yuh-Jier Mii helped develop the processes that led to the nanotechnology-based semiconductor chips found in today's computers. Edhem "Eddie" Custovic is working to combat food shortages by creating imaging technology that could allow plants to grow outside their native environment. Steven J. Sasson invented the first digital camera. The world would be a different place without their efforts.

During Mii's 30 years with Taiwan Semiconductor Manufacturing Co., he has worked on every generation of the company's integrated circuits. TSMC credits the senior vice president of research and development with helping it become the world's largest contract chip manufacturer. IEEE recognized Mii's contributions to logic process technologies and open innovation design platforms with this year's IEEE Frederik Philips Award [page 56].

Besides working to increase the production of food, Custovic is trying to boost the number of tech entrepreneurs. The IEEE senior member has established a foundation to provide adolescents in Bosnia and Herzegovina with educational opportunities, mentors, and scholarships. On page 52, learn more about this year's recipient of the IEEE Theodore W. Hissey Outstanding Young Professionals Award.

Thanks to Sasson, most people today have a digital camera—whether in their pocket or on their cellphone. The IEEE member invented the camera for Kodak in 1975. Sasson's prototype was about the size of a toaster, and it displayed its photos on a TV screen. For his invention, Sasson received the 2016 IEEE Masaru Ibuka Consumer Electronics Award. Earlier this year, the camera was commemorated with an IEEE Milestone [page 60].

Digital imagery has become important in the medical field. On page 63, learn about Embryonics, which aims to raise the in vitro fertilization success rate—around 45 percent today—by classifying images of embryos using deep learning to predict which ones are likely to result in successful pregnancies. The startup, cofounded by IEEE Fellow Alex Bronstein, hopes its system will help doctors create personalized treatment plans.

Many engineers are working on ways to address the global climate crisis, and IEEE is supporting their efforts. The Board of Directors recently formed an ad hoc committee to coordinate the organization's response. On page 54, read a Q&A with the committee's chair, 2022 IEEE President-Elect Saifur Rahman, who discusses issues it will be addressing and what roles IEEE members can play.

"IEEE has both the opportunity and the responsibility to assist in organizing engineers, scientists, and technical professionals to address the causes, mitigate the impact, and adapt to climate change," Rahman says. "It's just one more way in which engineers are working to change the world."

—KATHY PRETZ
Editor in chief, *The Institute*

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

PROFILE

Eddie Custovic Wants AI to End Hunger

The IEEE Young Professionals Award recipient is a born entrepreneur

BY JOANNA GOODRICH

LA TROBE UNIVERSITY

EDHEM "EDDIE" CUSTOVIC says he always wanted to leave behind a legacy. He's now doing so, in a number of ways.

The IEEE senior member established an innovation lab for budding entrepreneurs at La Trobe University, in Melbourne, Australia, where he is an engineering professor. He also set up a foundation to provide adolescents in his home country of Bosnia and Herzegovina with educational opportunities, mentorship, and scholarships. And if that isn't enough, he is working to combat impending food shortages by developing imaging technology to determine how to grow plants outside their native environments.

For his "leadership in the empowerment and development of technology professionals globally," Custovic is the recipient of this year's IEEE Theodore W. Hissey Outstanding Young Professionals Award. The award is sponsored by IEEE Young Professionals and the IEEE Photonics and Power & Energy societies.

Receiving the award is "by far the greatest achievement" in his career, he says. "It encompasses all the work that I've put in over the years in empowering young people to achieve more. It's particularly special to me because it bears the name of Theodore Hissey, someone who I find inspirational and have had the pleasure of working with on numerous occasions at IEEE."

Hissey, an IEEE Life Fellow and IEEE director emeritus, has supported the IEEE Young Professionals community over the years.

Born entrepreneur

Custovic says he has always been entrepreneurial.

"It goes back to being a refugee in Switzerland, where my brother and I had to learn how to earn money," Custovic says. He and his family fled Bosnia in 1991 because of ethnic violence there. They later moved to Australia.

Custovic's first big entrepreneurial venture began in 2010, while he was a doctoral student at La Trobe. While conducting research for his thesis, he noticed that there was little collaboration between disciplines at the university. It inspired him in 2016 to found the La Trobe Innovation and Entrepreneurship Foundry, which promotes multidisciplinary research among the school's faculty members and students, plus engineers in industry.

"We've had a lot of success through the lab," Custovic says. "Not only have participants developed various innovative technologies, but they have also gained interdisciplinary thinking."

Another one of Custovic's entrepreneurial ventures—the Bosnia and Herzegovina Futures Foundation, in Tuzla, Bosnia—hits closer to home.

"I grew up in a healthy environment and had the opportunity to pursue the career I wanted," he says. "But I couldn't stop thinking about the people who didn't have that same opportunity."

He started the foundation in 2015 with his brother, Resad, who is a civil engineer and also an entrepreneur. They wanted to create an organization that would be their "life legacy" and would help Bosnia and Herzegovina prosper by empowering youth through access to education and mentorship, as well as helping them develop technologies.

Almost 2 million Bosnians and Herzegovinians were displaced by the 1990s Bosnian War and now live in 30 countries worldwide, Custovic says. Inspired by IEEE's global membership, the two brothers created a network for them to collaborate on technology projects and mentor youths.

"My mentor Barry Shoop, who was the 2016 IEEE president, said that being a leader is about paving the way for others to succeed," Custovic says. "I've really taken that to heart."

Enough to eat

Custovic is working to make sure there's enough food to feed the growing human population. According to a study conducted by humanitarian organization Oxfam, Earth will run short of food by 2050.

Custovic is developing imaging technology that uses artificial intelligence to conduct plant phenotyping—or assessing a plant's expressed characteristics. By linking the automated assessments to each plant's genetic data, researchers can study the genetic changes that result in desirable traits such as drought-resistance or high-crop yields.

The research group at La Trobe is composed of engineers, geneticists, and plant biologists. It's also collaborating with several medicinal agriculture companies such as Photon Systems Instruments of Drasov in the Czech Republic. The company is leading the development of plant phenotyping technology worldwide.

"We have no more land available for agriculture," Custovic says, "so we now have to look at how we create efficiencies in growing food."

The team is also using the phenotype and genotype data to determine how to grow plants without the use of chemical fertilizers and pesticides. Fertilizers contain phosphorus, which pollutes groundwater and harms aquatic life.

The imaging technology will determine how to effectively grow plants—both for human consumption and medicinal use, he says, in environments where they wouldn't normally grow, as well as areas that have been severely impacted by climate change.

"It's an honor to work alongside so many talented engineers and scientists in developing technologies," he says, "and apply their capabilities that have the goal of saving, extending, and improving human lives."

Employer La Trobe University, in Melbourne, Australia
Title Engineering professor
Member grade Senior member
Alma mater La Trobe University

Custovic [seated, far right] with students from the La Trobe Innovation and Entrepreneurship Foundry.

EDDIE CUSTOVIC

A global network

In 2010 Custovic founded the IEEE student branch at La Trobe. He says his volunteerism in the organization "really took off from there." In 2014 he became secretary of the IEEE Victorian (Australia) Section and eventually served as its chair.

Custovic was a member of the IEEE Young Professionals committee from 2015 to 2017. He also served on the IEEE Publication Services and Products Board's strategic planning committee—first as the Young Professionals representative and then as a member-at-large—for six years. In addition, he was a member of the product development team, which explored potential offerings for members.

He was the inaugural chair of the IEEE Board of Directors' Industry Engagement Committee and oversaw the creation of the industry advisory board alongside other IEEE volunteers.

"It's exciting to interact with people who are working on solving different problems around the world," he says, "and not only learning about emerging technology but also creating a global network." ■

GETTY IMAGES

NEWS

IEEE's Plan to Help Combat Climate Change

BY KATHY PRETZ

THE IEEE BOARD OF DIRECTORS formed an ad hoc committee on climate change in February to coordinate its response to the global threat. *The Institute* asked the committee's chair, 2022 IEEE President-Elect Saifur Rahman, about the issues it will be addressing, what role IEEE members can play, and other topics.

His answers have been edited for clarity.

Why was the ad hoc committee established?
Rahman: Its charter is to develop a cross-IEEE strategy to synchronize and guide the organization's response to changes in the global climate. The committee will be the face of IEEE on the global platform dealing with these issues.

IEEE has significant relevant expertise and ongoing efforts that can be brought to bear on this issue.

The committee includes experts from all six IEEE organizational units and all 10 IEEE regions. I did this on purpose so that people will have some ownership over this problem. Efforts include the work done by societies, conferences, publications, and technical standards.

This ad hoc committee will serve to better connect and coordinate these efforts.

Why should IEEE be involved in combating climate change?
Rahman: IEEE has a global footprint, with members in 160 countries. With this very broad footprint, we can help to bring together organizations working on various aspects of climate change and possible solutions. IEEE is here to listen to them.

For example, organizations such as the Sierra Club and the World Wildlife Fund aspire to make the world carbon-neutral in 30 to 40 years. There's nothing wrong with their aspirations. We, as technologists, have a responsibility to point out to them the steps that need to be taken to get there and what the challenges are.

We are not a power company, a government, or a business that has a target to achieve, but a neutral platform. IEEE is highly respected because we don't have an agenda.

As the world's largest organization of technical professionals, IEEE has both the opportunity and the responsibility to assist in organizing engineers, scientists, and technical professionals to address the causes, mitigate the impact, and adapt to climate change.

What is the committee working on?
Rahman: We are reaching out to the French Academy of Technologies, Rotary International, UNESCO, U.S. National Academy of Engineering, World Federation of Engineering Organizations, and several environmental organizations to collaborate with them.

We are sharing each other's approaches to tackling the climate change problem, and IEEE is offering the services of its volunteer base to address some of these issues.

Why should members care about climate change? From a practical standpoint, what can they do?
Rahman: Climate change is an existential threat to humanity.

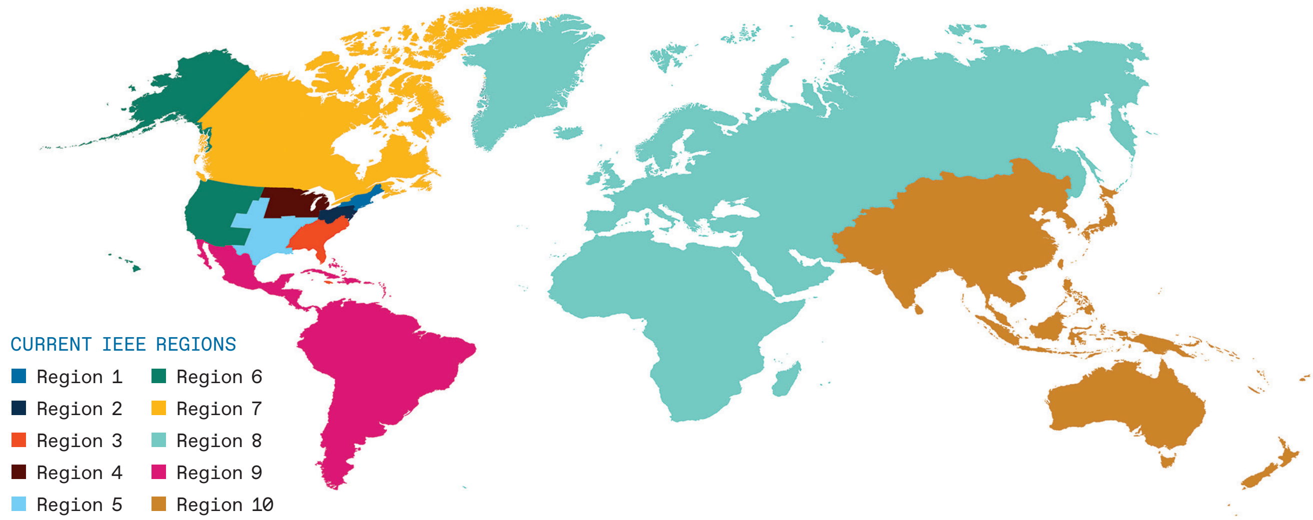
IEEE has a responsibility to bring this threat to the attention of our members so that they can in turn educate business leaders, political leaders, and society about its impact and possible solutions.

For example, engineers and technologists can develop technologies and offer best practices for decarbonization. IEEE can also provide resources to its members so they can give talks to local schools about topics such as coal-burning power plants or solar energy.

What are technologies that you think can affect climate change?
Rahman: When the ad hoc committee met for the first time in January, I identified what I call a six-point plan of approach to show that IEEE is thinking about climate change seriously.

The technologies are:

- Energy efficiency.
- Battery energy storage.
- Renewables such as solar, wind, and hydroelectricity.
- Nuclear power.
- Cross-border power transfer.
- Carbon sequestration.



IEEE NEWS

IEEE Is Working to Reconfigure Its Geographic Regions

IEEE HAS BEEN analyzing its region and geographic unit structure to ensure there is equitable representation across its global membership.

IEEE's region structure organizes membership into 10 globe-spanning geographic organizational units. Each member is assigned to a local section within one of the 10 regions, and each region elects a representative to serve on the IEEE Member and Geographic Activities (MGA) Board and on the IEEE Board of Directors. The regional units work to fulfill IEEE's mission and to meet the needs of IEEE members living within the region's borders.

As of June, the distribution of the IEEE membership across the 10 regions is Region 1: 24,938 members; Region 2: 21,795 members; Region 3: 24,202 members; Region 4: 16,836 members; Region 5: 22,317 members; Region 6: 43,089 members; Region 7: 14,179 members; Region 8: 74,451 members; Region 9: 16,426 members; and Region 10: 151,421 members.

Last year, the MGA Board, which oversees IEEE membership and the activities of geographic units worldwide, formed a region realignment ad hoc committee to review the regional organization and propose recommendations for structural changes. The committee consists of current region directors among other MGA volunteers.

Based on the ad hoc committee's recommendations, several actions have been taken to date. A formal plan will be presented to the MGA Board for approval at a meeting later this year.

- A plan has been developed to divide Region 10, IEEE's largest region, into two regions, to better meet the needs of its members in this region. Region 10 leadership and the MGA ad hoc committee have been working to develop the geographic boundaries of the two regions and have been creating implementation plans to execute this regional division following approval by the MGA Board and the IEEE Board of Directors.

- To maintain a total of 10 regions across the world, IEEE Region 1 and Region 2 are proposing to merge formally into a single region with a single region director. The Region 1 and Region 2 Board of Governors and Executive Committees will work collaboratively to document and determine the best path forward in merging the two regions' affairs, governance, and member activities.

- While planning efforts for regional realignment are ongoing, another recent initiative has been the introduction of additional zone representatives to the MGA Board. A zone is a substructure within a region with a significant number of members. In these large regions, zone representatives can assist in the region and provide an additional voice for members within the zone. To test the zone concept, in February the MGA Board approved the formation of four zones: two in Region 8 and two in Region 10. Representatives from the new zones participated in the MGA Board meeting held in June. The ad hoc committee is continuing to further develop specific responsibilities for the zone leaders.

The ad hoc committee is planning to bring motions forward at an upcoming MGA Board meeting to confirm the direction and next steps of the realignment, including next steps in the split of Region 10 into two regions, the consolidation of Regions 1 and 2 into a single region, and further definition of the zone concept.

If approved by the MGA Board, the vice president of MGA, David Koehler, will then present motions related to these matters for consideration by the IEEE Board of Directors at its November meeting. ■

PROFILE

TSMC's Yuh-Jier Mii on the Next Generation of Chips

The IEEE award recipient predicts the end of the chip shortage

BY KATHY PRETZ

Employer Taiwan Semiconductor Manufacturing Co.
Title Senior vice president of R&D
Member grade Member
Alma mater National Taiwan University

YUH-JIER MII STARTED on the ground floor of Taiwan Semiconductor Manufacturing Co. in 1994 as a fabrication integration manager. Today he's one of the Hsinchu-based company's leaders as senior vice president of research and development. During his nearly 30 years at TSMC, he has been involved with the creation of denser and denser integrated circuits.

The IEEE member is in charge of R&D for new chips built using TSMC's 3-nanometer process node, which recently began production. (The commercial term *nanometer* refers to a new, improved generation of silicon semiconductor chips.)

The world's largest contract chip manufacturer credits Mii with helping it maintain technology leadership in the foundry segment of the global semiconductor industry.

For his "leadership in developing industry-leading foundry logic process technologies and open innovation design platforms," Mii was honored with the 2022 IEEE Frederik Philips Award. He shares the award with his colleague Cliff Hou, TSMC's senior vice president of technology development and corporate research. The award is sponsored by Philips.

"It is my great honor to have received this award," Mii says. "I found out there were many outstanding leaders in this industry who have also received this award, such as Dr. Gordon Moore. This is also special for me because I received it with Cliff, who is doing the design part of the work. We work together to make the technology useful for our customers."

Bold move

Growing up, Mii was interested in physics, astronomy, and all kinds of science-related subjects, he says. Like most budding engineers, he liked to tear things apart to see how they worked.

"By nature, I was interested in doing engineering," he says. "Growing up in Taiwan, the environment encouraged people to become scientists or engineers."

Mii earned a bachelor's degree in electrical engineering from National Taiwan University, and his master's degree and Ph.D., also in EE, from the University of California, Los Angeles.

> "It's important for us to get talent and wisdom from the whole world."

He was hired in 1990 as a researcher at IBM's Thomas J. Watson Research Center, in Yorktown Heights, N.Y. During his four years there, he worked on IBM's 0.1-micrometer CMOS technology which, he says, had similar dimensions to the 90-nanometer technology he later worked on at TSMC.

Mii left IBM to join TSMC. It was, he says, a "big and bold move in many people's points of view—going from pure research to process integration in the manufacturing fab. But I think that was a good move for me and a very rare opportunity. I learned how fab operators work, what's in their minds, and what's required to make a technology manufacturable."

After learning the ropes as a fab integration manager, he was promoted to fab deputy director.

Then, in 2011, he was moved to R&D because several people had left, he says. His time as a researcher at IBM was about to pay off.

"Because I had some past research experience, I was transferred to R&D and managed the 90-nanometer program, and then the 40-nm," he says.

Later he was put in charge of the company's advanced technology development. The role involved defining the process technology and leading the team that would develop it for manufacturing nanotechnology-based semiconductor chips. They were the smallest transistors produced at the time.

Semiconductor challenges

One of Mii's most important challenges, he says, is determining the options for each technology that will bring the most value to TSMC's customers as well as deliver the solution in a predictable schedule. That was certainly true of the 3-nm node, which succeeded the 5-nm node just two and a half years later. The 3-nm node hit the market in June, and he's already working on the 2-nm version.

"We are approaching atomic scale," Mii says. "Before, we could achieve the next-generation node by fine-tuning the process, but now for every generation we must find new ways in terms of transistor architecture, materials, processes, and tools. In the past, it's pretty much been a major optical shrink, but that's no longer a simple trick."

Early in his career, developing a new process technology meant just shrinking the transistor using better lithography. But it requires more innovation now, he says.

The semiconductor shortage is another hurdle he has had to face. In his personal opinion—not necessarily that of TSMC—it is going to take two to three years to bring new fabs online to resolve the situation. He partly blames the COVID-19 pandemic for disrupting the global economy, but the growing pervasiveness of electronics in daily life is also causing a surge in semiconductor demand.

He says the industry missed signs that demand was growing. However, he says, the field learned a lot from the situation, and he expects it will do better in the future.

"Right now, the industry is investing a tremendous amount of capital into building extra capacity to solve this chip shortage problem," Mii says. "We have a much clearer picture of future demand today than we had two years ago."

He adds that finding enough talented engineers is another concern.

Wisdom from the world

Mii joined IEEE as a grad student at UCLA.

"As an EE student, it was natural to join IEEE," he says, "because that's the portal for people to exchange information and learn."

He's still in IEEE to learn, he says.

"Developing technology by ourselves is not enough," Mii says. "In my leadership role, it's important for us to get the talent and the wisdom from the whole world, not just from the team in Taiwan." ■

TSMC

CAREERS

10 Takeaways From How Steve Jobs Approached Work

BY SAN MURUGESAN

ENGINEERS, IT PROFESSIONALS, and business executives can learn valuable lessons by studying Steve Jobs' career.

Here are 10 strategies that I've identified that can help a wide range of professionals excel.

- **Think differently and work persistently**
- **Anticipate and create the need**
- **Create a vision and innovate**
- **Focus on design**
- **Engineer software and hardware together**
- **Get your priorities straight**
- **Embrace multidisciplinary perspectives**
- **Pay attention to details and strive for perfection**
- **Keep improving**
- **Master your communication**

San Murugesan is director of Brite Professional Services, former editor in chief of *IT Professional*, and former editorial advisory board member of *The Institute*.

IEEE PRODUCTS

AI-Powered Platform Aids Telecom Product Designers

BY KATHY PRETZ

THE NEW IEEE DiscoveryPoint for Communications platform provides one-stop access to searchable, curated content from trusted sources on just about every telecommunications topic. Its library contains more than 1 million full-text research documents; 10,000 technical standards; 8,000 online courses; 400 e-book titles; 18 million parts and various solutions from manufacturers and distributors; and 1,100 industry and product news bulletins, blogs, and white papers.

The documents come from reputable organizations including AT&T, F5 Networks, the IEEE Xplore Digital Library, the International Telecommunication Union, River Publishers, Qualcomm, SMPTE, and Verizon.

The subscription-based product's intuitive search engine zeroes in on key concepts related to the topic being searched for. To get started, the user types a word, phrase, concept, author or company name, or another term into the search bar. The search engine's ranking algorithm analyzes the full text and the metadata of the documents to find relevant material.

The results are organized into channels and categorized by type of material, such as research papers, standards, books, or industry news. For each search result, a machine-learning feature examines the document and generates a short summary of key points, which are highlighted in the document.

Search results can be sorted by relevance or by time period, starting with the previous 90 days and going as far back as 10 years for journals and five years for conferences. The results also can be grouped, for example, by a publication's name. Searches can be saved, and users can bookmark documents.

IEEE DiscoveryPoint also recommends content based on an automated analysis of the user's reading activity during the previous 30 days. Users can set up email alerts for new content that fits their search criteria.

The subscription price is based on the size of the organization and how many engineers and technical professionals will be using it. To request a demo, visit the IEEE DiscoveryPoint for Communications website at discoverypoint.ieee.org. ■

DANIEL ACKER/GETTY IMAGES

Attendees at a recent IEEE Women in Engineering International Leadership Conference in Austin, Texas.

IEEE NEWS

IEEE Women In Engineering Celebrates 25 Years

BY JOANNA GOODRICH

IEEE WOMEN IN ENGINEERING, formed 25 years ago, now has more than 35,000 members and 1,000 affinity groups worldwide. WIE facilitates the recruitment and retention of women in technical disciplines around the world. It also works to inspire girls to pursue a career in engineering. Both women and men can join.

To mark its anniversary, the group held competitions, panels, seminars, and other events. It also established an award to honor men who actively advocate for diversity and inclusion in science, technology, engineering, and math fields.

Celebrating steady growth

WIE's greatest accomplishment is its continuous growth, thanks to enthusiastic members, Cinzia Da Vià says. The IEEE senior member oversaw the anniversary celebrations. She says the events were created to highlight the work of WIE members as well as affiliated affinity groups.

Celebrations kicked off in December with a virtual panel that featured past WIE chairs including Lisa Lazareck-Asunta, Ramalatha Marimuthu, and Mary Ellen Randall. They explained why they joined the group, and they shared their experiences as chair.

On International Women's Day, 8 March, a 12-hour virtual marathon showcased each IEEE region's diversity and inclusion efforts.

WIE "is enormous, so we wanted to give our members the opportunity to meet each other and know what each region is doing," Da Vià says. Both sessions are available on demand on IEEE.tv at ieeetv.ieee.org/channels/wie.

During the yearlong Extraordinary Women Extraordinary Science Seminar Series, each month two WIE members present their work. Presentations to date have covered entrepreneurship, technology for the benefit of humanity, and space exploration. The talks are available on demand at ieee.org/wie25seminarseries.

Women's careers often are interrupted by caretaking responsibilities, and the COVID-19 pandemic has made the situation worse due to shutdowns of day care centers and schools, Da Vià says. There also has been an increase in the number of women who died by suicide during the pandemic, she says, as well as more domestic violence and sexual assaults.

To help find solutions, WIE launched the W-to-W Tech Ideas Dedicated to Women competition. The contest sought technologies that could be used to help with child care, and to provide easier access to mental health services as well as protection against abuse.

Komal Shah and Manish Arora won for their system for using adaptive stimulation to treat urinary incontinence in women. They presented the technology at the IEEE WIE International Leadership Conference. The hybrid event was held in June.

Women working in STEM fields are often cheered on by extraordinary men, says Jenifer Castillo, chair of WIE. To recognize them, the Behind a Successful Woman awards were established. The eight recipients will be featured in the December issue of *WIE Magazine*.

Diversity and inclusion programs

WIE also has been working on several diversity and inclusion initiatives. The group recently pledged to work toward gender-diversified panels at all IEEE meetings, conferences, and events, including its own. Castillo says it's important for conference attendees to feel represented by those on panels.

The group also is working to increase the number of female IEEE senior members. Senior member is the highest grade for which IEEE members may apply. One proven way to boost the number of female senior members is by holding elevation drives just for women.

Castillo says her hope is that 25 years from now, there will be no need for such initiatives.

"Hopefully," she says, "companies and organizations will be naturally diverse and inclusive." ■

HISTORY

The First Digital Camera Was Kodak's Biggest Secret

The toaster-sized device displayed photos on a TV screen

BY JOANNA GOODRICH

IN THE PAST two weeks, you've probably shared at least one embarrassing photo with family or friends. The process, from taking the photo to sharing it, was practically instantaneous. Yet only 20 years ago, you would have had to load and unload film in your camera, drop the film off for processing, and then wait days before you'd know if you even had any images worth sharing.

Digital cameras have been around a lot longer than you might think, however. Invented in 1975 at Eastman Kodak in Rochester, N.Y., the first digital camera displayed photos on a TV screen.

The Kodak digital camera has been commemorated as an IEEE Milestone.

"This was more than just a camera," IEEE Member Steven J. Sasson, inventor of the device, told *The New York Times* in 2015. "It was a photographic system to demonstrate the idea of an all-electronic camera

IEEE Member Steven J. Sasson, inventor of the first digital camera, compares it with Kodak's EasyShare One camera.

DAVID DUPREY/AP

that didn't use any consumables in the capturing and display of still photographic images."

Sasson says he never anticipated how the imaging of everything would become so ubiquitous.

"Photos have become the universal form of casual conversation," he said in a 2018 interview with *The Institute*. "And cameras are present in almost every type of environment, including in our own homes."

It took only 50 milliseconds to capture an image with the camera, but it took 23 seconds to record it to a cassette tape.

Completing a difficult task

Eastman Kodak wanted to find a way to digitize images using a charged coupled device—specifically Fairchild Semiconductor's 100-by-100-pixel CCD. The company assigned the job to Sasson in 1974, when he joined Kodak as an electronics engineer working in the apparatus division's research lab.

CCDs, which were invented in 1969 by Willard Boyle and George E. Smith at Bell Labs, consist of a sensor that converts an incoming two-dimensional light pattern into an electrical signal that in turn becomes an image. In the case of Fairchild's CCD, the image would be a square: 100 by 100 pixels.

Although the CCDs could capture an image, they couldn't store it. So Sasson built a CCD into a camera with RAM to capture image data, which was then transferred to a cassette tape. In a 2016 interview with *DIY Photography*, he said cassettes were the only permanent form of "digital storage" available to him at the time. He designed it so each tape would store 30 images.

To build his digital camera, Sasson scavenged a lens and an exposure mechanism from a Kodak XL55 movie camera. They served as his camera's optics and were enclosed in a blue, rectangular box. The box had a switch on the side that turned the device on and off and served as the camera's shutter release.

The blue box sat atop a layer of a half dozen circuit boards and 16 AA batteries. Enclosed in an open steel frame, all of the parts could be seen. The frame also could unfold to make it easier to modify the camera. A portable Memodyne cassette recorder that was attached to the side of the frame held the tape. The camera weighed 3.6 kilograms and was about the size of a toaster.

The photographer flipped the switch once to turn on the camera and flipped it a second time to take a photo. The CCD would capture the image, which would then run through a Motorola analog-to-digital converter and be stored temporarily in a DRAM array of a dozen 4,096-bit chips. The image was then transferred to the cassette.

Sasson and his colleagues invented a device to take the information stored on the tape and turn it into digital images. This playback unit converted the data to a standard NTSC signal so the images could be displayed on a TV screen.

After a year of working on the camera, Sasson took his first photo in December 1975. It was of a Kodak lab technician, Joy Marshall.

"It only took 50 milliseconds to capture the image, but it took 23 seconds to record it to the tape," Sasson said in the 2015 *Times* article. "I'd pop the cassette tape out, hand it to my assistant, and he would put it in our playback unit. About 30 seconds later, up popped the 100-pixel-by-100-pixel black-and-white image."

But when Sasson displayed the photo on the lab's computer, the image's flaws were apparent. The camera could render shades that were clearly dark or light, but things in between appeared as static, according to a 2020 *IEEE Spectrum* article about digital cameras. Therefore, Marshall's face was not visible in the photograph.

Sasson fixed those problems and was granted a U.S. patent for the camera in 1978, but it was never put into production.

Even after a few demonstrations of how the camera worked, Kodak executives said they didn't see a market for it. Sasson wasn't allowed to publicly talk about the camera or show his prototype to anyone outside of Kodak, according to an article about the camera on *The Vintage News*.

That didn't deter Sasson, who continued to build more cameras for Kodak. In 1994 he built one of the first commercially available digital cameras—the AP NC2000—in collaboration with Nikon.

Today Sasson's original digital camera is on display at the Smithsonian Institution's National Museum of American History, in Washington, D.C.

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

The IEEE Rochester (N.Y.) Section sponsored the nomination for the digital camera. ■

Kodak executives said they didn't see a market for the camera. Sasson wasn't allowed to talk publicly about it or show his prototype to anyone.

IEEE PRODUCTS

Courses on Aerospace and Defense Technical Standards

BY JOHANNA PEREZ

As the world tries to recover from the COVID-19 pandemic, the aerospace and defense industries are predicted to grow from US $416 billion to $551 billion by 2030, according to Mordor Intelligence.

The growth means increased development of aviation, space, and other systems that are crucial to the industries. The use of technical standards can ensure that critical software and components that run the systems are reliable and secure.

To help systems engineers, software engineers, and people working on back-end systems, IEEE Educational Activities and the IEEE Standards Association partnered to create a five-course program: IEEE Software and Systems Engineering Standards Used in Aerospace and Defense.

The courses offered in the program are:

Life Cycle Processes

From this course, learners will better understand engineering concepts, be able to select and apply systems and software engineering standards, and employ special considerations for critical programs.

Implementing DevOps Best Practices

This course discusses the required development and operations practices for building reliable and secure systems both in general and in regulated environments.

Verification and Validation of Systems, Software, and Hardware

Learners explore the basic concepts, purposes, and benefits of verification and validation in software and hardware covered in IEEE Std. 1012.

Software Testing Driven by Standards and Models

This course provides an overview of the IEEE 29119 series of standards. It teaches how the standards can be applied during the software life cycle, with an emphasis on aerospace and defense purposes.

ISO/IEC/IEEE 29119 for Software Testing

This series of courses explores the five steps taught in the Software Testing Driven by Standards and Models course. The series provides details on the five supporting parts of the IEEE 29119 series of standards, from proposal to retirement. Included are processes, documentation, testing techniques, and keyword-driven testing.

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

Visit the IEEE Learning Network website (iln.ieee.org) for member and nonmember pricing.

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

Love Brainteasers? Then Check Out IEEE Puzzlers

BY NATALIE APADULA

PUZZLES HAVE BEEN proven to exercise the brain, improve memory, elevate IQ, increase productivity, and boost mood.

IEEE Puzzlers was created by volunteers to offer a fun, engaging virtual experience for those who enjoy solving brainteasers such as missing numbers and logic games—at varying levels of difficulty.

The Puzzlers program, which is accessible to members and non-members on IEEE Collabratec, celebrated its one-year anniversary in May.

What began as a whimsical initiative snowballed into a movement, with more than 3,000 participants to date.

IEEE Puzzlers offers more than 100 logic games and math-related puzzles.

People who correctly solve the brainteasers can receive badges and recognition on the website.

There are several types of badges, based on how many puzzles users solve. A badge is awarded when participants solve 7, 15, 30, 50, and 75 puzzles. New badges are slated to be released soon.

IEEE Student Member Melissa Akiki, a logic game creator, says she wanted to create a "nonmath puzzle genre" for brainteaser lovers who would rather not solve mathematics-related puzzles.

"The experience in general has been very rewarding," Akiki says, "and the team was wonderful, always open to new ideas."

IEEE Puzzlers collaborates with a number of IEEE programs and operating units, including Women in Engineering, to create games and contests.

Teachers have used the program's brainteasers in class as warmups and icebreakers for students.

If you are interested in collaborating with IEEE Puzzlers, email puzzlers@ieee.org.

Natalie Apadula is the product marketing specialist for IEEE Collabratec.

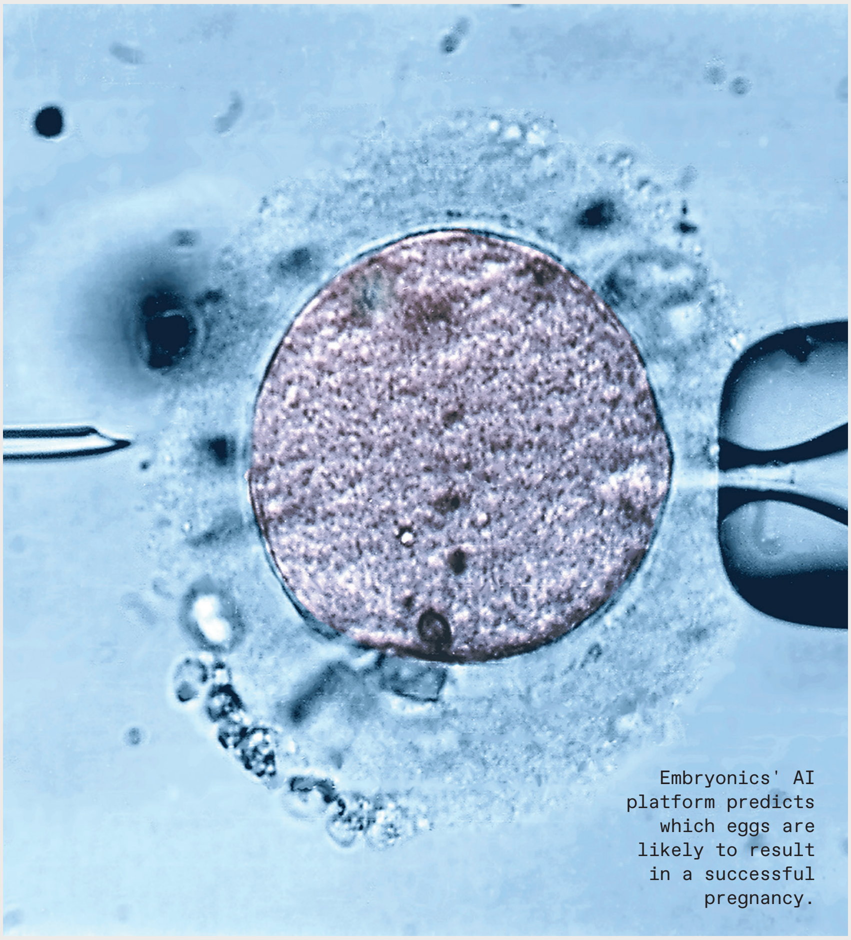
IEEE PUZZLERS/ISTOCKPHOTO

STARTUP

AI to Help Increase the IVF Success Rate

Clinical tests show up to a 50 percent improvement

BY JOANNA GOODRICH



Embryonics' AI platform predicts which eggs are likely to result in a successful pregnancy.

ZEPHYR/SCIENCE SOURCE

ALTHOUGH IN VITRO fertilization (IVF) techniques have advanced significantly in recent decades, the average success rate is still fairly low: around 45 percent. The percentage steadily declines as people age; a 40-year-old person has a likely success rate of about 12 percent, according to Pregnancy & IVF Clinics Worldwide.

Embryonics, a startup in Haifa, Israel, aims to raise the IVF success rate with its suite of AI algorithms. The company's system uses machine learning to help doctors create personalized treatment plans.

"Technology can help fertility doctors make data-driven decisions and answer complex questions in a smarter way," says Dr. Yael Gold-Zamir, CEO and cofounder. She launched the company in 2018 with David Silver and IEEE Fellow Alex Bronstein.

Gold-Zamir has a medical degree from the Hebrew University of Jerusalem. Silver is a machine learning engineer who previously worked for Apple and Intel. Bronstein is a computer science professor at the Technion.

"Embryonics is tackling very unique problems—the quality of human analysis and how to analyze big data so that it is clinically relevant," Bronstein says.

IVF primer

In IVF, several mature eggs are retrieved from the patient's ovaries. The eggs are then mixed with sperm in a clinic. The developing embryos grow in the lab for several days until an embryologist chooses one or two to be implanted. (The term *embryo* technically refers to the developmental stage, when the amniotic sac forms inside the uterus, around two weeks after fertilization. But fertility clinics typically refer to the clusters of cells that they evaluate and implant as embryos.)

Doctors typically choose which embryos to implant based on chromosomal testing and appearance, Silver says. Each is graded based on the number and size of its cells and its rate of development.

But there are several problems with that approach, Silver says.

Dr. Yael Gold-Zamir and David Silver, two of Embryonics' founders.

"One is that the embryologists' ability to collect data is limited," he says. "The amount of data about embryos, past patients, and successful live births available to any single doctor is very small, so it's hard for them to generalize [about] what indicates that a fertilized egg is viable."

Another problem is that not all clinics have the same grading system, so two facilities might rate the same embryo differently.

One of the startup's algorithms uses deep learning to classify images of the embryos and predict which ones will result in a successful pregnancy. It compares the patient's medical information, such as age and underlying health conditions, along with images of her embryos, to the same data from past patients who had successful or unsuccessful implantations.

Silver and Bronstein used thousands of medical images from around the world to train the AI system. But while developing the algorithm, the engineers found that clinics don't have the same equipment or use the same settings on microscopes and other tools. The variation affected how the platform classified the embryos.

To overcome that problem, Bronstein and Silver developed their own data-augmentation system for the images. It cancels out environmental factors such as lighting and removes irrelevant parts of the images.

"The system only extracts information that is biologically meaningful, such as cellular structures," Silver says.

The algorithm was tested in clinics in several countries including Lithuania, Malaysia, and Spain. It has increased the success rate by 25 to 50 percent, Silver says.

The embryo-classification system is available in Asia and Europe. The company has submitted its algorithm to the U.S. Food and Drug Administration for approval.

Embryonics is developing an algorithm to help doctors prescribe the best hormone-replacement treatment for patients who require it to increase their chances of successful implantations. There are currently no definitive guidelines to help doctors decide which medication is best for patients, Silver says.

"We found that sometimes the same patient goes to several clinics and is prescribed completely different hormone treatment plans," he says.

To improve decision-making for the treatment plan, the Embryonics team is developing an algorithm that uses machine learning to provide customized recommendations. The algorithm is learning from information about patients as well as a collection of past treatment plans and their outcomes.

"Based on similarities among patients, we can do simulations," Silver says, "and estimate what would have happened if another treatment protocol was chosen."

"IVF is complicated," Gold-Zamir says. "It's not just one decision doctors have to make; it's a process of sequential decisions. And we need to maximize the potential for the success of all of those decisions."

Improving outcomes

The startup emerged from Gold-Zamir's belief that technology can help doctors make better decisions and therefore increase IVF success.

"Many complicated decisions are made based on the doctor's gut feeling, which is based on all the cases they have seen in their career," she says. The decisions include which embryos are viable, how many should be implanted, and what kind of hormone treatment is most appropriate.

Gold-Zamir was introduced to Bronstein and Silver through a colleague. Although their original goal was simply to publish a research paper, the trio wanted to improve fertility outcomes and decided to commercialize their first algorithm.

Initial funding for the company came from friends and family, but the team later received a grant from the Israel Innovation Authority, a government agency that helps fund technology startups. Gold-Zamir says the grant enabled them to launch the company.

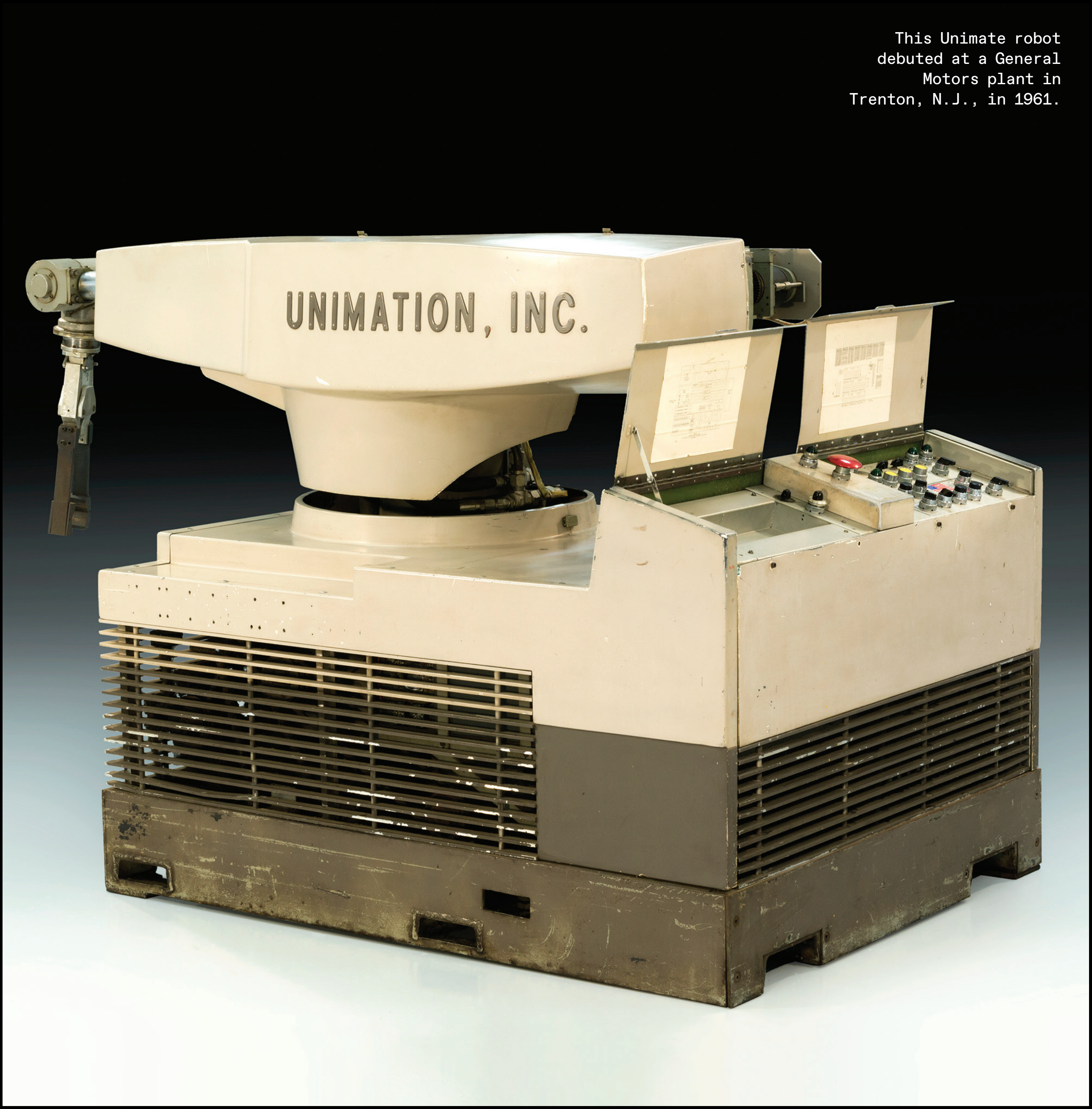
The founders also participated in the Google for Startups program, which provides companies with funding, mentoring, and networking.

Its next goal is to develop algorithms to help doctors choose which embryos to freeze for future IVF cycles as well as noninvasive genetic screening and analysis.

"I love being able to apply the latest and greatest technologies to something that impacts human life in one of the greatest ways possible: starting a family," Silver says. ■

BY ALLISON MARSH

Past Forward



This Unimate robot debuted at a General Motors plant in Trenton, N.J., in 1961.

THE HENRY FORD

Unimate Punches In

On a fateful day in 1961, this Unimate took its place on the assembly line of General Motors' Ternstedt plant, in Trenton, N.J. It took over the dirty, dreary, and dangerous job of unloading the finished castings from a die-cast press. Its debut was not particularly glamorous or impressive, but it earned the Unimate a place in history as the first successful application of an industrial robot. Workers didn't object to this initial use of a robot, but when GM launched its first spot-welding line of 28 robots in 1970 at the Lordstown, Ohio, plant, they revolted. ■

FOR MORE ON THE HISTORY OF THE UNIMATE, SEE spectrum.ieee.org/pastforward-sep2022