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FOR THE TECHNOLOGY INSIDER | 07.18

The Tube That Will Not Die

The colorful past—and surprising future—of the **Nixie tube**, the world's most enduring display technology P. 36

IEEE

On the cover **Photograph by Dalibor Farny**

PHOTOGRAPH BY The Voorhes

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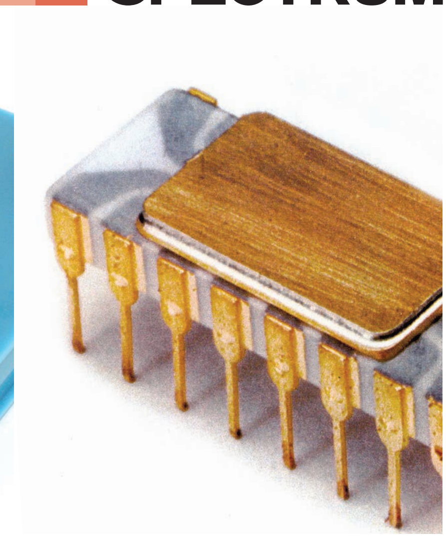

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Welcome, Class of 2018!
IEEE Spectrum's Chip Hall of Fame is admitting five inductees: The Intel 4004 and RCA 1802 CPUs helped push computing into the everyday world, while the Nvidia NV20 GPU serendipitously kick-started the machine-learning revolution. The PB-100 sensor made it possible to put a camera in every phone, and the TDA7000 made it possible to put an FM radio into…well, everything. Visit the hall at https://spectrum.ieee.org/static/chip-hall-of-fame

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ROBOTIC MERMAID IEEE Life Fellow Oussama Khatib, a professor at Stanford, invented a swimming humanoid. OceanOne can dive to 100 meters below sea level, a depth that's too dangerous for humans.

OCEANIC ENGINEERING SOCIETY The IEEE group dedicated to the advancement of maritime technology was named a society 35 years ago.

A DAY IN THE LIFE We interviewed an oceanic engineer to learn more about the field and how to break in.

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FROM LEFT: SOLIDENERGY SYSTEMS; DAVID SCHNEIDER; INTEL

THAT SPECIAL GLOW

JENS BOOS WAS AN IMPRESSIONABLE 15-year-old when he encountered his first Nixie tube. The year was 2005, and Boos was visiting the Heinz Nixdorf MuseumsForum, in Paderborn, Germany. The teenager liked the various displays on computer history well enough, but what really caught his eye was a set of four Nixie tubes, glowing orange as they cycled through the first few hundred digits of pi.

He was enchanted. Nixie tubes are like that for some people. The exhibit's accompanying placard gave no information about the tubes, so Boos hit the Internet. "I didn't even know what they were called, so I searched on 'glowing number display,' 'orange number counter,' things like that." He soon discovered the tubes' distinctive name, the fact that they hadn't been manufactured since the early 1990s, and also a lively online community of Nixie collectors.

As his passion for Nixies grew, Boos corresponded with fellow enthusiasts around the world, accumulated product literature, and even tracked down a few of the engineers who'd worked on the original devices in the 1950s. Everything he learned, he posted on his personal website. He even tried making his own Nixies. "All I ever managed was to get two wires into a glass tube, seal it off, and evacuate it. The residual nitrogen gave this hazy violet sort of glow." (Above, Boos holds a ZM1040.)

Boos had to curtail his tube-related activities when he began pursuing a Ph.D. in theoretical physics, as a Vanier scholar at the University of Alberta. But when *IEEE Spectrum* invited him to write about Nixie tubes [see p. 36], he gladly agreed. He drew on his personal files, as well as records from the Charles Babbage Institute and notes from *Spectrum* executive editor Glenn Zorpette, another Nixie fan.

"People in the Nixie community regularly share information about what they've learned," Boos says. "I wrote the article, but I couldn't have done it without the help of many other people." ■

JENS BOOS

CONTRIBUTORS_

Carlos Abellán

Abellán, CEO of the quantum cryptography startup Quside, fell in love with cryptography while in college. "I took all the courses I could on crypto," he recalls. After taking a class taught by Valerio Pruneri of the Institute of Photonic Sciences, he began working in Pruneri's group on quantum-source devices. In "The Future of Cryptography Is Quantum," the two discuss how quantum random-number generators could finally enable unbreakable encryption [p. 30].

Susan Karlin

Karlin is a longtime *IEEE Spectrum* contributor who covers the nexus of science, technology, and the arts. In this issue, she profiles computer scientist Charles Petrie, who helps run the ephemeral, but very busy, airport at the annual Burning Man festival [p. 18]. "The amount of logistics, planning, and coordination to erect and run a fully functioning, FAA-compliant airport in the middle of nowhere for two weeks a year is stupefying," says Karlin.

Prachi Patel

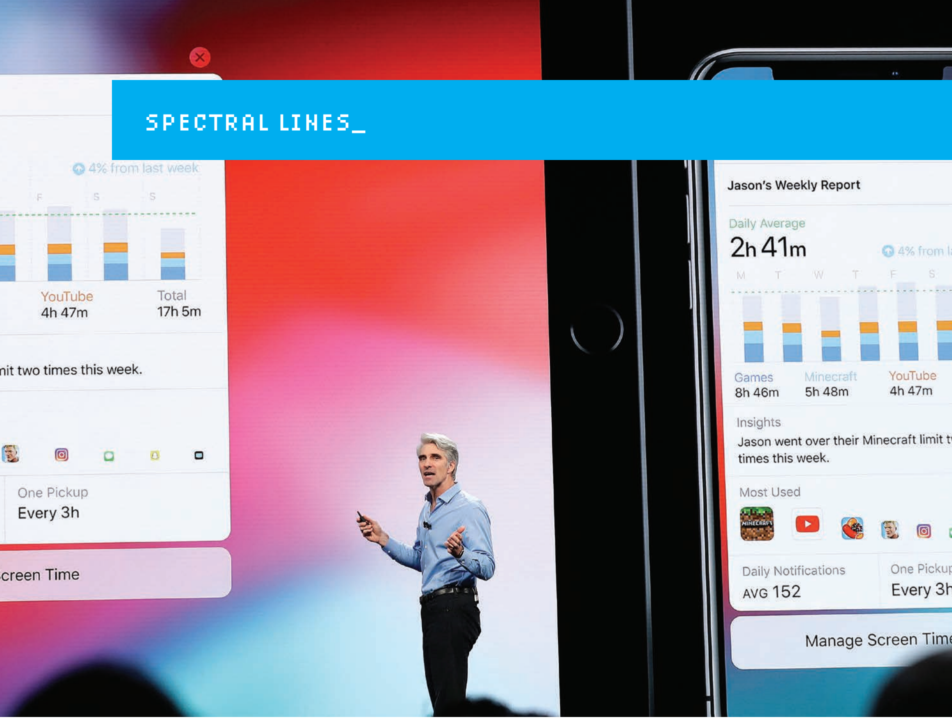
Pittsburgh-based contributing editor Patel writes in this issue about a new type of lithium-ion battery [p. 7]. "Batteries are this key technology that's going to drive us toward clean cars, and wind and solar," she says. Patel is now shopping for her first electric car–either a Nissan Leaf or a Chevy Bolt. She'll charge it with the grid-connected solar array installed on her house last year, which produces more power than her family can use.

Michael Pecht

Pecht, an IEEE Fellow, majored in acoustics before veering off to electrical engineering for a master's degree, and then to engineering mechanics for a Ph.D. He's now at the University of Maryland, where he directs the Center for Advanced Life Cycle Engineering and works to make electronic devices safe and reliable. Lithium-ion batteries, he notes, are a particular danger: They can literally blow up in your face, as he discusses in "When E-Cigarettes Go Boom" [p. 42].

Andrew Whitehead

Whitehead wants to make electric vehicles more efficient. He and Chris Hilton, a colleague at Protean Electric, describe one way to do that in "In-Wheel Motors Roll Again" [p. 24]. Whitehead began his engineering career working on race cars, including a stint with Honda's F1 racing team. About 10 years ago, he decided that he "should do something more sustainable," so he joined Protean Electric and has been helping to improve electric cars ever since.



Addicted to Your Smartphone? Welcome to Apple Rehab

Apple announces tools to help you put your phone down

We've all been there: You're out with friends for dinner and everyone has finished their entrees and placed orders for coffee and dessert. The conversation seems to fade along with the food and, almost simultaneously, everyone suddenly realizes they have to give their phones a quick peek—any text messages? And as long as it's in their hands, maybe a glance at email or Facebook. The scrolling goes on until the coffee arrives. ¶ Every time this happens, I feel like sneezing, because it reminds me of the era in which the end of a meal had at least a few people at a table reaching for a pack of cigarettes and a lighter. ¶ It's not that people didn't recognize early on that phones don't belong at the dinner table. Five or six years ago, Silicon Valley VCs and entrepreneurs were seen, on occasion, playing the so-called Phone Stacking Game. At lunches and dinners out with a group, attendees would stack their phones in the center of the table—first person to touch a phone pays the bill. It didn't catch on widely, and eventually faded away—I'm guessing because it was just too painful for people to sit at a meal, staring at their phones without being able to touch them. ¶ Last month, Apple announced a set of tools designed to help people break phone addiction. If that's even possible at this point (the jury is still out), Apple's approach is smart. It turns putting down the phone—or avoiding certain apps and behaviors—into a competition with yourself. In the same way that Fitbit and its kin got us taking an extra walk or two around the block to make our step goals, Apple's addiction-fighting tools could just motivate real behavioral change. (Apple, of course, is quite confident we'll never give up our smartphones altogether, and that helping us to use them less won't hurt sales at all.) ¶ Here's how Craig Federighi [above], Apple's senior vice president for software engineering, described the tools. He spoke during the keynote at Apple's Worldwide Developers' Conference, held in San Jose, Calif., last month.

Do Not Disturb: I already use Apple's Do Not Disturb function at night; it's an easy swipe up that silences all alerts, but it can be set to allow calls from your Favorites and repeated calls from the same number. Right now, notifications are silent but pile up on your lock screen. The new version of Do Not Disturb will suppress those lock-screen messages until you enable them, so if you grab your phone during the night, you won't see them and, as Federighi put it, "get spun up." The new Do Not Disturb includes timing and geofencing features, so you can set it for an hour, say, or until you leave a certain location. (At this point, the screen in the presentation showed a parent at a park ignoring a child. Enough said.)

Notifications: An update to notifications will allow people to modify those settings from the lock screen. In other words, at the exact moment when you're thinking, "Why on earth am I getting these stupid alerts?," you can permanently turn off those alerts.

Screen Time: Here's where the addiction controls get serious. Your phone will give you a weekly report of how you are using your device, including how much time you spend in various apps, what apps send the most notifications, and how often you pick up your phone, much like a fitness tracker's weekly report. If you think you're overusing the phone or particular apps, you will be able to set limits. As you use the app, you'll be alerted to how much time you have left. When the time is up, you won't be able to get back to the app without jumping through hoops. I think this is going to be a real wake-up call for many of us. And yes, I intend to use it—I do feel that I pick up my phone way too much.

Parental controls: This feature is Screen Time on steroids—parents will be able to get activity reports detailing their children's phone use, and they'll be able to create allowances for overall screen time and for individual apps or categories of apps. A burst of applause followed this announcement. I know my efforts to control screen time with the practically nonexistent tools of the past were pretty much useless. If I still had young kids, I'd be cheering for this one, too. —TEKLA S. PERRY

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

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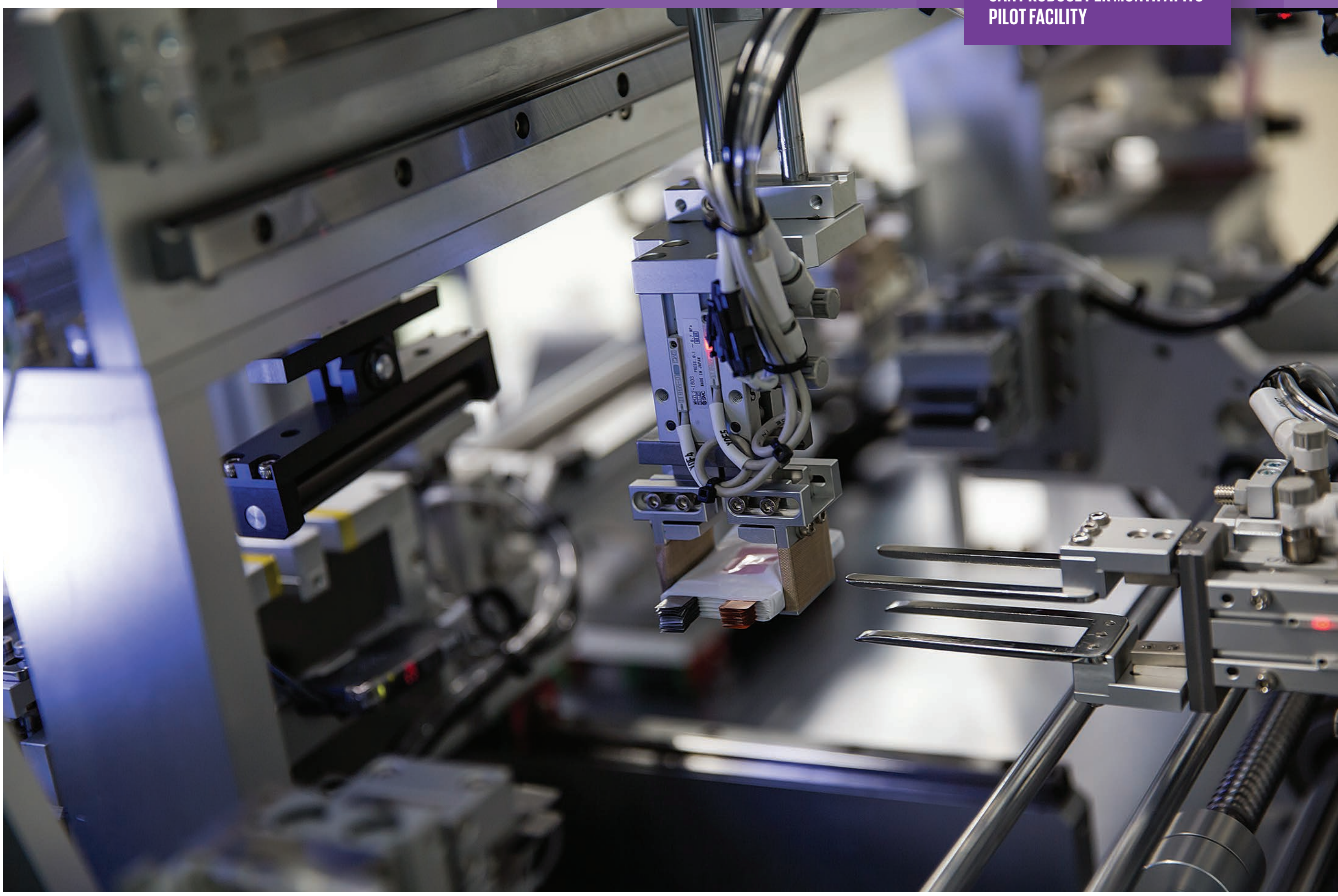
MARCIO JOSE SANCHEZ/AP

NEWS

5,000: NUMBER OF SEMISOLID BATTERY CELLS SOLIDENERGY CAN PRODUCE PER MONTH AT ITS PILOT FACILITY



READY-MADE: SolidEnergy says its new batteries can be manufactured with existing equipment.

SOLIDENERGY SYSTEMS

NEW BATTERY TECH LAUNCHES IN DRONES

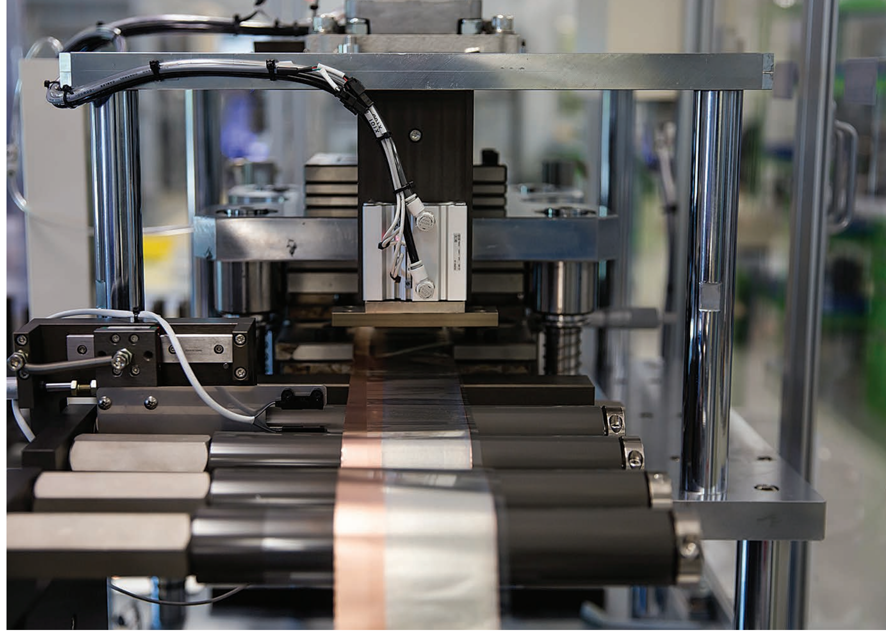
SolidEnergy Systems will put safer lithium batteries in drones this year, in cars after 2021

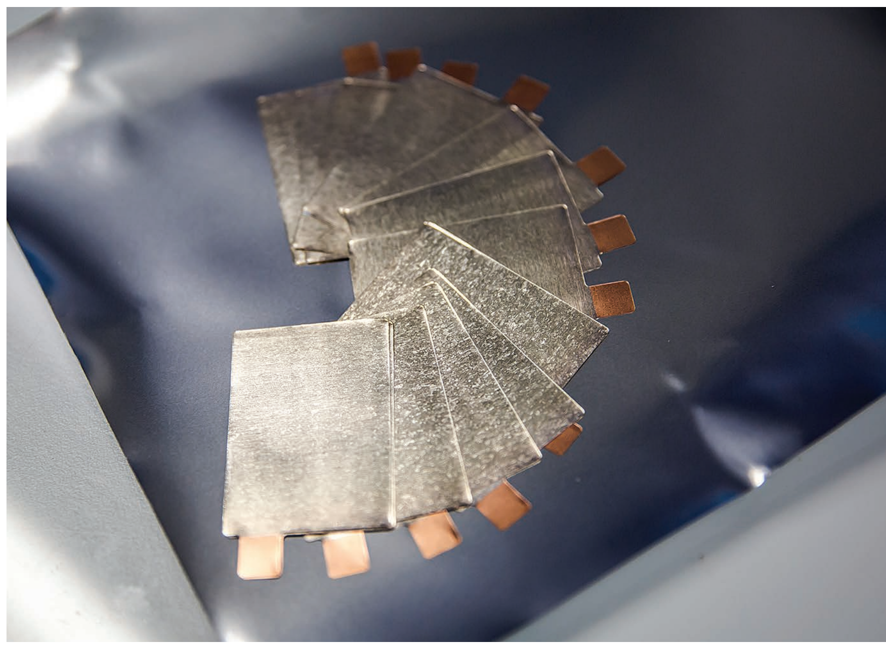
Lithium-ion batteries boast a powerful blend of energy capacity and long cycle life. But they have a dangerous tendency to burst into flames, leading to injuries, product recalls, and flight bans.

Researchers have touted solid-state lithium batteries as a safer alternative. These devices swap out flammable liquid electrolytes for an inert solid such as plastic or ceramic. But researchers have pursued solid-state battery technology for decades without coming up with any products.

Now, SolidEnergy Systems, in Massachusetts, plans to become the first company to sell such batteries. The startup says it can pack twice as much energy into its battery as a conventional lithium-ion battery of the same weight can store.

That means devices could work twice as long. For example, right now "advanced drones have sensors, cameras, and processors on board, so the battery lasts only 20 minutes, »





WEED CONTROL: These ultrathin anodes, made of pure lithium foil, are covered in a polymer-ceramic coating to prevent harmful dendrites from sprouting.

SOLIDENERGY SYSTEMS (2)

and it's heavy," says founder Qichao Hu. With SolidEnergy's new battery, those drones could fly for 40 minutes or more.

The company is currently testing its batteries for drones and expects to begin selling them later this year, followed by batteries for wearables in 2019 and for electric vehicles after 2021.

In today's batteries, a dilute solution of lithium salts serves as the electrolyte. Its job is to shuttle ions between the carbon anode and the lithium transition metal oxide cathode. Some ceramics, polymers, and glassy materials can also do that well. In addition to being safer than their liquid counterparts, these alternatives could also support a pure lithium anode, which would boost energy density.

Lithium-ion battery pioneers originally chose lithium metal for the anode in the 1980s. But lithium metal anodes quickly grow mossy whiskers called dendrites, which can reach the cathode and short the battery. So battery researchers switched to carbon for the anode.

SolidEnergy's workaround is to coat its ultrathin anode, made of a pure lithium foil, with a mixed polymer-ceramic electrolyte, which smothers dendrite growth. Another electrolyte, a paste of lithium salts, goes on the cathode.

The electrolyte on the cathode contains just enough solvent to make the lithium salts conduct ions at room temperature. The device is technically a semisolid battery but safer than conventional lithium-ion cells, Hu says. The battery's energy density is about 500 watt-hours per kilogram, twice that of a conventional lithium-ion battery's 250 Wh/kg. The downside is that it can be recharged only about 200 times, as opposed to more than 1,000 times for conventional batteries.

"There are lots of people trying to find the 100 percent perfect solid-state approach," Hu says. "But we think our semisolid approach is good enough."

Other labs remain focused on that vision of the ultimate solid-state battery. Last year, John Goodenough at the University of Texas at Austin unveiled a solid glass battery. He and colleague Maria Helena Braga use a lithium-doped glassy material as the electrolyte. In their latest design, which they reported in April in the *Journal of the American Chemical Society*, they coat the flexible cathode with a special plasticizer solution.

One problem with solid-state batteries is that as various materials expand and contract at different rates, the batteries' interfaces crack. The plasticizer acts as a cushion to prevent cracking, Braga says. The new battery design has twice the energy density of conventional lithium-ion batteries and can be recharged 23,000 times.

Recently, industry giants have also begun to invest in solid-state batteries. Honda, Nissan, and Toyota have teamed up with Panasonic Corp. to develop them for electric vehicles. But some high-profile buyouts of solid-state technology startups have sputtered.

In 2015, Dyson bought University of Michigan spin-off Sakti3 with plans to develop an EV battery, while German giant Bosch bought Seeo, a solid-state polymer battery startup from Lawrence Berkeley National Laboratory (LBNL). Both companies have since deserted those technologies.

Lithium metal batteries are not easy to work with, says LBNL scientist and chemical engineer Nitash Balsara, who cofounded Seeo with other LBNL alumni in 2007. "By and large, the battery industry is really interested in safety, as long as it's free," he says. "I think [that's] a mistake. There is room to develop intrinsically safe lithium batteries and give [them] to consumers."

Balsara now has a new startup, Blue Current, which is perfecting a hybrid polymer-ceramic electrolyte. Polymers don't conduct ions as well as ceramics, but ceramics are brittle. The hybrid "mixes the best of both worlds to stuff more energy into a battery, and it doesn't crack when a car hits a bump," Balsara says.

Solid-state batteries might work eventually, but they still face engineering challenges, says lithium-ion pioneer M. Stanley Whittingham, a professor of chemistry at Binghamton University, in New York. "Nothing's going to replace lithium-ion batteries in the near future," he says, predicting that solid and semisolid batteries will be relegated to niche markets for the next 5 to 10 years. "In the end, the challenge is how expensive they'll be," he says.

At $500 per kilowatt-hour, SolidEnergy's battery is currently much pricier than conventional lithium-ion batteries, which now sell for about $200. But Hu expects costs to go down with large-scale manufacturing and is talking with major battery makers.

"We're not ready for the ultimate goal of EVs yet," Hu admits. "But we've met the key performance requirements for drones and are making great progress toward EV batteries." —PRACHI PATEL

POST YOUR COMMENTS at https://spectrum.ieee.org/semisolidbattery0718

3 SENSORS TO TRACK EVERY BITE AND GULP

These technologies could make it easier to watch what you eat

People looking to track their diets and count their calories can choose from dozens of apps designed to help them do just that. But using the apps properly requires a lot of effort.

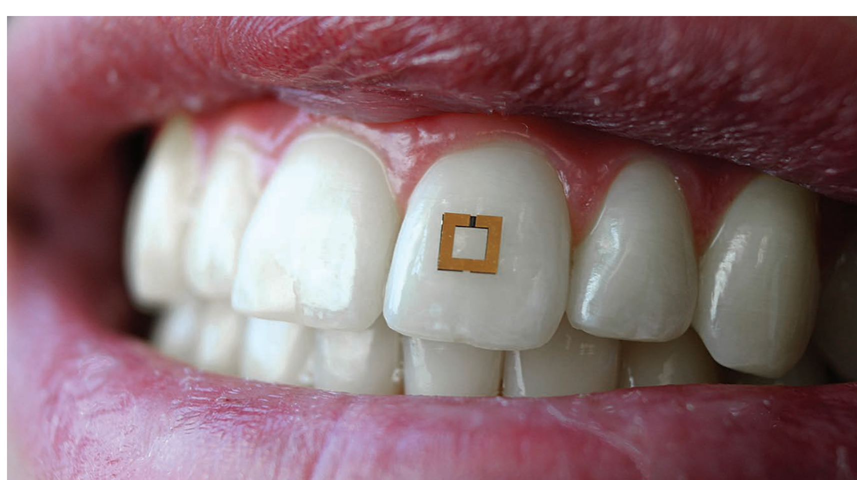
"There's a huge problem with self-reporting," says Edward Sazonov, a professor of electrical and computer engineering at the University of Alabama, who has worked on a number of food tracking systems. "Imagine that you're passing by the kitchen at work and there's a bowl of strawberries, and you grab a couple. Are you going to pull out your smartphone and take a picture, then enter the information that you just ate three strawberries?" And if the bowl is full of candy bars instead, he adds, most app users are even less likely to record it.

That's why researchers are developing passive devices that monitor eating behavior. As long as people wear the device, the tech takes care of the rest. Researchers are experimenting with sensors that directly record food going into the mouth and down the gullet, and they hope to eventually turn their lab gizmos into commercial products.

THE AUTOMATED INGESTION MONITOR

Sazonov's latest invention, which he's describing at the meeting of the IEEE Engineering in Medicine and Biology Society this month, detects the muscle motions involved in every chew. The gadget clips onto a pair of eyeglasses, and it contains two sensors: a strain sensor that presses lightly against the temple to monitor the contractions of the temporal muscle, and an accelerometer that picks up the subtle movements of the jaw. When the system detects food intake, it triggers a tiny camera (also tucked into the gadget) to take a photo every few seconds, thus creating a time-stamped visual record of the food consumed.

Sazonov says the ingestion monitor captures detailed information



SAY CHEESE: This sensor sticks to the uneven surface of a tooth to monitor the wearer's glucose, salt, and alcohol intake.

SILKLAB/TUFTS UNIVERSITY

about a person's eating patterns: "It measures how fast someone is eating, and how many chews they take for each bite," he says. He wants to create a consumer device that can deliver this information to users in real time and thus help them change their food habits. "Some eating behavior is automatic," he says. "Imagine you're sitting in front of the TV next to a bowl of chips–you grab the chips and shove them into your mouth," he says. "Our sensors could help people be more mindful."

SODIUM SENSOR

With more than 1 billion people around the world now living with high blood pressure–a major risk factor for heart disease and strokes–doctors are keen to get people to reduce their sodium intake. But sodium, the primary component of table salt, is everywhere in our modern diets–it's in snack foods, in restaurant meals, and in beverages. Even when people want to follow doctors' advice, they may not realize how much sodium they're taking in.

W. Hong Yeo, an assistant professor of micro- and nano-engineering at Georgia Tech, is tackling the problem with a flexible electronic sodium sensor that sits in the mouth. His first prototype is battery powered and embedded in a dental retainer: "We wanted to offer easy handling and cleaning capability," he says. But future versions could do away with the battery, instead receiving power remotely via inductive coupling, and could be small enough to stick directly to the tongue or a tooth. When users gulp down tomato juice or crunch on potato chips, the sodium sensor sends info via Bluetooth to their smartphones, giving them instant data about whether they're busting their low-sodium diets.

> "Our sensors could help people be more mindful"
>
> — Edward Sazonov, University of Alabama

DENTAL ANTENNA

A research team from Tufts University's department of biomedical engineering designed a tiny tooth-mounted device that can monitor people's consumption of all sorts of toothsome things, including alcohol, salt, and sugar.

Fiorenzo Omenetto led the team that developed the sensor, which is composed of an inner layer of polymer film sandwiched between two gold rings that act as antennas. When the film absorbs certain chemicals, such as ethanol, sodium, and glucose, it swells and pushes the gold rings apart. Each substance causes the film to thicken up to a different degree, so the distance between the gold rings indicates which chemical passed over the tooth. Omenetto's system bounces radio waves off the tooth and records the spectrum and intensity of the wave that returns from the antenna. While alcohol, salt, and sugar are high on the list of problematic foods that consumers want to track, the sensor's film could theoretically be tuned to detect all manner of different comestibles.

—ELIZA STRICKLAND

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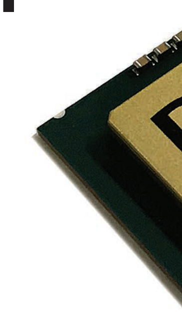
SILICON CHIP DELIVERS QUANTUM SPEEDS

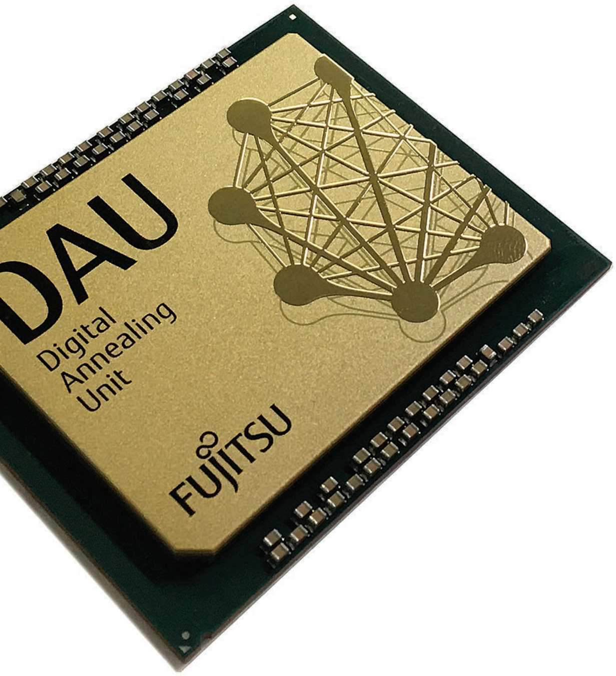


Fujitsu says its Digital Annealer will outperform today's commercial quantum computers

Fujitsu has designed a new computer architecture running on silicon–dubbed the Digital Annealer–which the company claims rivals quantum computers in utility. Fujitsu began offering cloud services in Japan in May, employing the technology to resolve combinatorial optimization problems, such as finding similarities among patterns of molecules to speed drug discovery.

The service comes as activity in the quantum computer field ramps up. D-Wave Systems, based in Burnaby, B.C., Canada, is marketing its latest 2000Q quantum annealing computer and is racing to introduce a 5,000-qubit model within the next two years, according to industry press reports. Quantum annealing is a mathematical tool designed to find a good solution to a complex optimization task that has more possible answers than conventional computing can manage.

Meanwhile, companies and research institutes are creating "universal" quantum computers. These use quantum gates to handle quantum bits, or qubits, and run more sophisticated algorithms than quantum annealing machines can. However, given the design of these universal computers and requirements for highly controlled superconducting envi-



MONEY MAKER: Fujitsu's new chip will support cloud services anticipated to generate US $900 million in revenues by 2022.

FUJITSU

ronments, the number of qubits these machines can practically support is relatively small at present, typically up to 50 qubits, compared with D-Wave's 2,000 qubits.

IBM and Microsoft are taking this quantum gate approach, while Google is working on both quantum gate and quantum annealing systems. In 2016, IBM made its 5-qubit superconducting quantum computer available online for researchers. Since then, IBM has also made 16-qubit and now 20-qubit machines available. At CES 2018, Intel unveiled a 49-qubit superconducting quantum test chip called Tangle Lake.

While all these approaches have the potential to deliver unprecedented computing power, quantum computers require a lot of overhead and have expensive price tags. They must maintain near absolute zero temperatures and remain free from magnetic interference, thermal noise, and mechanical vibration in order for qubits to maintain superposition—the ability to hold dual states of 0 and 1—which forms the basis of quantum calculations.

Fujitsu, working with the University of Toronto, has developed its Digital Annealer as an alternative to current quantum annealing computers, such as the D-Wave machines. Whereas the latter requires a carefully controlled cryogenic environment, Fujitsu employs conventional semiconductor technology that operates at room temperature and can fit on a circuit board small enough to slide into the rack of a data center.

The Digital Annealer is a dedicated chip that uses non-von Neumann architecture to minimize data movement in solving combinatorial optimization problems. It is composed of 1,024 "bit-updating blocks" with on-chip memory that stores weights and biases, logic blocks to perform "bit flips," and interfacing and control circuitry, explains Hirotaka Tamura, a Fujitsu senior fellow.

Unlike classical computers, the Digital Annealer doesn't require programming. Rather, a problem is uploaded in the form of weight matrices and bias vectors so as to convert it into an "energy landscape." Fujitsu has teamed up with 1QB Information Technologies, a leader in quantum computing software based in Vancouver, B.C., to provide the software for the system and a development kit for customers, so they can write their own energy landscapes.

To solve a problem, "each bit block uses its one-to-all connections via the 1,023 weights stored in memory," explains Tamura. The Digital Annealer makes full use of this parallelism to assume many possible states based on the weight matrices and bias vectors. Then, the bit blocks collectively run a stochastic search—an estimation technique to minimize the value of a mathematical function—to produce candidates for the next sequence in the process. This continues until the lowest energy state in the energy landscape is realized.

Hidetoshi Nishimori, a professor of physics at the Tokyo Institute of Technology and an author of one of the first papers proposing the idea of quantum annealing, explains the operation by way of analogy: "In digital annealing, the system hops from one state to another sequentially in search for better solutions, like a person wandering around a complicated landscape filled with hills and valleys, looking for the lowest point." This is in contrast, Nishimori adds, with quantum annealing, "where the system looks for the best solution in a massively parallel way with all the states taken into account simultaneously."

So is the CMOS-based Digital Annealer, with its 1,024 bit blocks capable of matching or outperforming the D-Wave quantum annealing system, with its 2,000 qubits, as Fujitsu claims?

"At the moment, most likely it can," says Nishimori. He notes that the weights between bit blocks on the Fujitsu machine enable a problem to be expressed with a higher degree of precision than the D-Wave system has. Nevertheless, "quantum annealers will surpass the Digital Annealer in the long run because of their supermassive quantum parallelism," he adds. Meanwhile, Fujitsu says it aims to introduce a Digital Annealer with 8,192 bit blocks next year, followed by a 1-million-bit block machine later.

Fujitsu is working with the University of Toronto to research applications for the Digital Annealer, and later this year, the company will begin marketing Digital Annealer servers, towers, and chips for on-site installation. Fujitsu also plans to roll out cloud services in North America, Europe, and Asia before the end of the year and is targeting 100 billion yen (about US $900 million) in revenues for the service by 2022. —JOHN BOYD

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

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WALL STREET TRIES SHORTWAVE RADIO

Financial firms hope radio can execute transatlantic trades faster than fiber-optic cables

MYSTERY TOWER: Bob Van Valzah spotted this strange cell tower during a bike ride in West Chicago. Soon after, he began to investigate.

In 2010, the company Spread Networks completed a fiber-optic cable linking two key trading hubs: Chicago and New York (or rather New Jersey, where Wall Street has its computerized trading equipment). That cable, built at a cost of some US $300 million, took the most direct route between those two points and shaved more than a millisecond from what had formerly been the shortest round-trip travel time for information: 14.5 milliseconds.

That tiny time savings was a boon for high-frequency financial traders, who could take advantage of it to buy or sell before others learned of distant price shifts. This strategy, called latency arbitrage, has driven a technological arms race in the trading world, with companies competing to send information from one trading center to another in the minimum possible time.

The next salvo came shortly after Spread Networks' cable started pulsing with light. Companies such as McKay Brothers built special microwave links between those same two trading centers. As anyone who has taken Physics 101 knows, electromagnetic waves travel much faster through air than glass, so with properly engineered radio equipment, microwave signals can readily beat out light in glass fiber.

A similar battle appears to be taking place now across the Atlantic, where information to guide lucrative trades traditionally flows through fiber-optic submarine cables, the fastest of which—the Hibernia Express—was built in 2015.

No, trading companies are not planning an array of microwave towers on buoys across the Atlantic. But they seem to be pursuing the next best thing—using shortwave radio to transmit information across the ocean the old-fashioned way.

Shortwave radio is venerable technology, dating back to the early part of the 20th century. Radio amateurs, often called hams, use it to contact one another around the world with modest equipment. So it's surprising, really, that high-frequency traders have only lately begun to take advantage of this technique.

Most of the evidence that traders are pursuing this approach comes from Bob Van Valzah, a software engineer and networking specialist who characterizes himself as a "latency buster." By chance, he stumbled on an odd-looking cell tower in West Chicago, near where he lives, and after much investigation (which he detailed in a blog post) concluded that the giant antennas sprouting from it were sending signals about goings-on at the Chicago Mercantile Exchange to trading centers in Europe.

Who exactly is using this link? If you dig through the Federal Communications Commission's online license database, you can find that although the official license for that West Chicago cell tower was awarded to one company, the "real party in interest" is IMC, a technology-driven trading firm that has invested in McKay Brothers and thus is no stranger to the value of low-latency radio links.

And this is not the only example. "There are three different companies that have built million-dollar cornfields," says Van Valzah, referring to giant shortwave antennas located on agricultural lands near Chicago. Exactly what frequencies they are using to transmit and how often is anyone's guess. If he were more ambitious, Van Valzah says, he'd get a spectrum analyzer and put up a pup tent next to one of those antennas to find out.

As any radio amateur will tell you, communications on shortwave, or high-frequency (HF) bands, is an iffy affair, because these long-distance transmissions depend on the configuration of the ionosphere, which in turn depends on such factors as time of day and the intensity of sunspots.

Even if the integrity of the link itself were not a problem, those traders will have to contend with much lower bandwidth than they are used to. That means that they won't be able to transmit very much information about price shifts—perhaps just a few bytes at a time (presumably well encrypted). If they try to send more at the lower data rates that shortwave affords, the time required will wipe out any latency gains over communications by fiber.

Still, with low-orbit satellites not able to provide such fast communication links and lots of money to be made this way, it makes good sense that high-frequency traders are giving shortwave a try. What remains a mystery, though, is why they didn't attempt this many years ago. —DAVID SCHNEIDER

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

POST YOUR COMMENTS at https://spectrum.ieee.org/shortwavestocks0718

BOB VAN VALZAH

PHOTOGRAPH BY Lionel Bonaventure/AFP/Getty Images

HIGH AND DRY

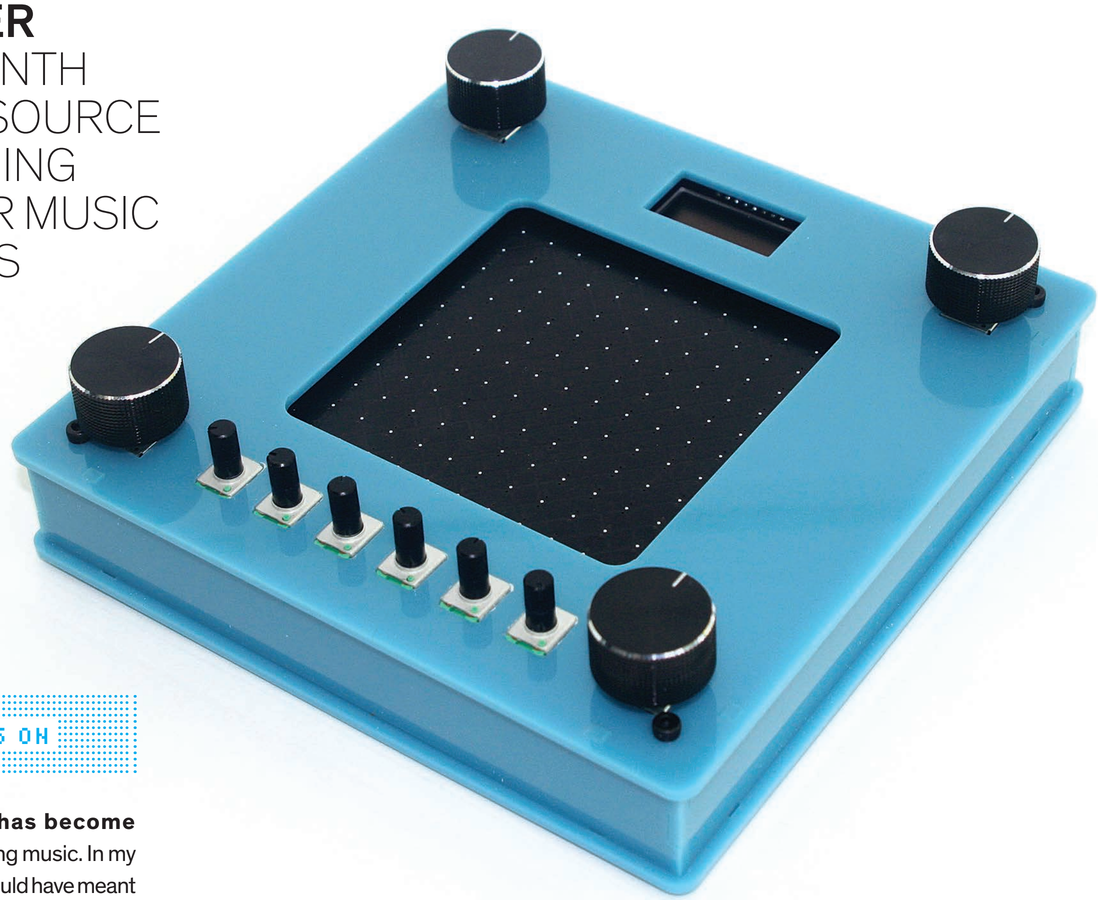
FLEET VEHICLES are usually where new driving technology is tried out first. That is true for self-driving technology, which Uber wants to use to shuttle people along city streets. But taxis may also be first to test new tech for water travel. The vessel seen here during testing in May and June on the Seine river, in Paris, is known as a SeaBubble. The battery-powered, four-passenger craft doesn't glide through the water like a traditional boat. Hydrofoils that jut up from beneath the vessel, propelled by electric motors, let it race along, with its hull flying above the water's surface, at speeds of up to 50 kilometers per hour.

RESOURCES

86 BILLION: THE CURRENT BEST ESTIMATE FOR THE NUMBER OF NEURONS IN THE HUMAN BRAIN

BUILD A NEURAL SYNTHESIZER

GOOGLE NSYNTH IS AN OPEN-SOURCE DEEP-LEARNING PROJECT FOR MUSIC ENTHUSIASTS



DAVID SCHNEIDER

RESOURCES_HANDS ON

My teenage son has become interested in making music. In my generation, that would have meant picking up an electric guitar and forming a garage band. Instead, he's installed a digital-audio workstation on his laptop, studied up on music theory, and started composing "EDM," or electronic dance music. Frankly, I don't understand what he's doing.

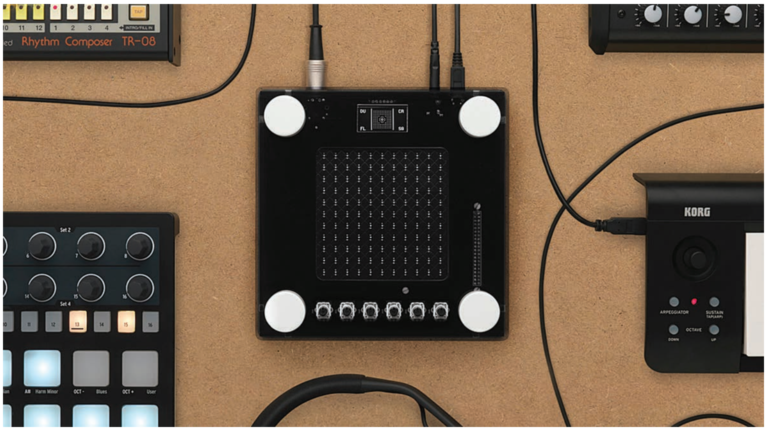
I would much prefer that he spend some of his free hours honing his programming skills, and I keep suggesting that he explore one of the machine-learning frameworks now available. Although he's expressed interest and has started to explore Torch, he's not found anything that would make him really dive in.

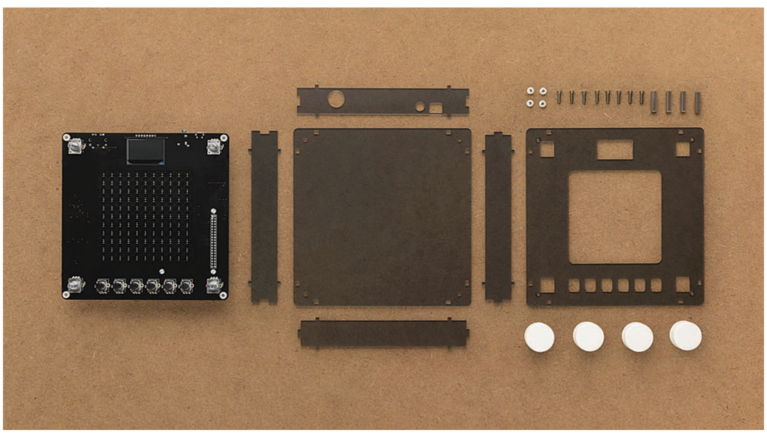
So, while I'm not musical myself, my eyes lit up when I stumbled on Google's new neural music-synthesis project NSynth (Neural Synthesizer). This, I thought, might be just the ticket to get my music-giddy son hooked on the amazing things possible with machine learning.

NSynth uses a deep neural network to distill musical notes from various instruments down to their essentials. Google's developers first created a digital archive of some 300,000 notes, including up to 88 examples from about 1,000 different instruments, all sampled at 16 kilohertz. They then input those data into a deep-learning model that can represent all those wildly different sounds far more compactly using what they call "embeddings." That exercise supposedly took about 10 days running on thirty-two K40 graphics processing units.

Why do that? Well, with those results, you can now answer a question like "What do you get when you cross a piano with a flute?" (Musicians: Insert joke here.)

It would, of course, be easy enough to add together the two very distinct sounds of each instrument playing, say, middle C. But that would just sound like the two instruments playing the same note at once. NSynth allows you to combine the two sets of embeddings and create a virtual piano-flute, the sound of





MUTANT MUSIC MACHINE: Google's NSynth Super can create the hybridized sounds of multiple instruments [top]. The hardware consists of a Raspberry Pi and a special PCB, which both go in an acrylic case [bottom].

GOOGLE (2)

which can be synthesized using NSynth's neural decoder.

What's more, the Google team designed a piece of open-source hardware called NSynth Super, which allows you to combine as many as four instruments at once. I figured that building the synthesizer and experimenting with it would be a perfect father-son project.

Alas, my son isn't particularly adept with hardware, so construction fell mostly on me. Google posted a good set of instructions, so putting it together was fairly straightforward.

I ordered a premade printed circuit board (PCB) for the project, which cost US $20 on Tindie, making it considerably less expensive than it would have been had I tried to have this rather large board fabricated myself. The same vendor sells a $60 version fully populated with its many surface-mount components, but it was out of stock.

So I ordered the bare board and components separately. On Hackaday, I found a complete bill of materials with links to suggested suppliers, which was handy. Still, a few parts were hard to procure. In particular, the rotary encoders used to assign instruments were unavailable, but I couldn't see any harm in substituting the 12-indent-per-revolution versions the design specified with 18-indent versions of the same part.

Soldering the surface mount components required a magnifier and tweezers along with the usual flux, wick, and solder. Once I'd assembled all the components, the next step was to acquire the huge 62-gigabyte image file of the NSynth software to put on the SD card of a Raspberry Pi 3, which plugs into the board and provides the bulk of the synthesizer's computational power. That took many hours to download, but the operation otherwise went smoothly. It was also straightforward to download the firmware for the processor embedded in the NSynth Super that handles user inputs.

Indeed, it all seemed too easy—until it came time to test the thing. The first hurdle was finding a source of MIDI signals to play, MIDI being the industry standard for controlling and playing digital instruments. My son has a MIDI-enabled keyboard, but I discovered that it has no dedicated MIDI output: It just has USB, over which MIDI data packets are transmitted. (Normally, MIDI uses a hardware interface that electrically isolates instruments from incoming signals to prevent interference from ground loops.) So I created a dedicated output-only MIDI source for testing, using an Arduino and a couple of resistors.

I was excited to plug everything together for a test but was quickly disappointed. I heard nothing at all. Many hours and much head-scratching later, I found the problem—a bad connection on one of the pins of the NSynth Super's digital-to-analog converter, which was sitting a little above the board.

After fixing that issue, it was time to put the NSynth Super PCB into its enclosure. For that, I had earlier ordered an acrylic sheet to be laser cut, which required rearranging the various parts in Google's Adobe Illustrator file so that things fit on the sheet sizes used by the fabrication house I chose (Ponoko). While ordering the electronic components, I had also gotten the various screws, spacers, and knobs needed. So I had everything on hand, and it was easy enough to involve my son in final assembly.

My son and I spent some late-night hours bonding over the Arduino code needed to get his MIDI keyboard to output true MIDI signals. And we can now tell you how a piano-flute sounds: Awful. Indeed, most combinations of instruments sound pretty bad, at least to me. My son, on the other hand, is more taken with some of NSynth Super's weird electronic sounds, especially the ones you can dance to. **—DAVID SCHNEIDER**

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/nsynth0718

GIVING BURNING MAN ITS WINGS

FOR ONE WEEK A YEAR, CHARLES PETRIE HELPS RUN ONE OF NEVADA'S BUSIEST AIRPORTS

READY FOR TAKEOFF: Each year, an airport springs into existence in the desert. Charles Petrie [top right] has helped it scale dramatically.

Most people know Burning Man as the 70,000-strong end-of-summer experimental arts festival in Nevada's Black Rock Desert. Lesser known is its FAA-designated airport. The Black Rock City Municipal Airport springs up each year to coordinate nearly 3,700 general aviation, chartered, and scenic flights carrying some 6,000 passengers in and out of the gate.

It's been nearly two decades since the airport, founded in 1999 by pilot Lissa Shoun, began as a single dusty landing strip handling tens of flights. Computer engineer Charles Petrie was instrumental in transforming it into Nevada's third busiest airport (behind Las Vegas's McCarran and Reno-Tahoe airports) during 7 of its 13 operating days.

Petrie worked in early artificial intelligence at the now-defunct Microelectronics and Computer Technology Corp., in Austin, Texas. At Stanford University, he served from 1993 until retiring in 2011 as a computational-logic research scientist and executive director of the Stanford Networking Research Center. He was also the founding editor of *IEEE Internet Computing*. Petrie's first "burn," in 1998, came the year after a motorcycle rally he was in took him past Burning Man. "I saw all these costumed people coming off a bus and said, 'That's what I want to do next year.' "

Petrie is notoriously accident-prone, with repeated injuries earning him the nickname "Calamity." "I'm the only person who's ever been medevaced twice from Burning Man!" he says with a laugh.

In the earliest days, things at the Burning Man airport were very informal. "It started off as this little flying club with a few hundred passengers. We had to scale it to its current size," says Petrie. "I've worked to preserve this community, but it's gotten very complicated, very difficult. People just see a bunch of planes parked next to tents and don't realize there are all these processes and procedures in place."

Petrie joined Shoun when she started the airport in 1999 and played an increasingly important role. Over the years, they developed progressively complex operating and safety manuals, and Petrie designed an accompanying software system to track flights and passengers, as well as rogue charter flights and fence jumpers.

When Petrie took over as airport manager after the 2012 festival, he and his team streamlined the chains of command for its 400 volunteers and instituted more stringent rules and systems—including special tests and briefings for pilots flying in the playa's mercurial winds as well as ways to catch and penalize trespassers.

"This is the great freak attractor out here," says Petrie. "We have pilots who don't think rules apply to them, the naked guy throwing stones at planes and climbing in the cockpits..."

"Every plane, pilot, and passenger out there is documented," he adds. "If we find an undocumented plane, we impound it. Pilots either fly safely or we ground them. The [U.S. Bureau of Land Management] says we're one of the strictest organizations they've ever seen."

In 2016, Petrie and his team boosted passenger capacity by convincing Burning Man to hire an umbrella company to fly larger planes and oversee the 17 individual charter companies that make up the event's Burner Express Air, which shuttles burners from six midsize airports in California and Nevada. The goal is to enable the airport to eventually handle 5,000 attendees to reduce the extreme road traffic to Burning Man, says Petrie.

"My whole theory of project management is, you don't have a plan, you have 'dependencies.' When something changes, you find out what else changes. It's a propagation-of-change model. I'm constantly touching base with everyone, making sure everything gets done," says Petrie.

Approaching his 21st burn, Petrie is slowing down, having transferred command of the airport to its former logistics manager, Meg Kosowski. But he'll still be there in the desert, serving as an on-site mentor. **—SUSAN KARLIN**

POST YOUR COMMENTS at https://spectrum.ieee.org/airport0718

SUSAN KARLIN (2)

WHERE THE JOBS ARE: 2018
THINGS ARE GREAT—IF YOU'RE A NEW GRAD

Employers in the United States plan to hire 4 percent more new graduates from the class of 2018 than they did from the class of 2017, according to the National Association of Colleges and Employers. And when it comes to competing for jobs, newly minted engineers have the power to punch well above their weight.

The engineering industry is responding to a wider "device-driven economy, in which we're pushing to make everything as mobile as possible," says Anthony Del Preto, manager of engineering division operations at the recruitment firm Aerotek. He pegs the top opportunities for class of 2018 EEs to medical devices and robotics, autonomous and other vehicles, wearables, and the Internet of Things.

These sectors depend on complex embedded systems talking to one another, and that's changing the face of engineering, Del Preto says, thus making prior experience less valuable. No longer does the hardware engineer do his job and the software engineer hers, with the systems team pulling everything together at the end: "Instead, the [EEs] with the greatest opportunity will be the hardware engineer with a software background, or the software engineer with electrical experience," he says.

The blending of job responsibilities is clear in the jobs Caltech grads are taking, says Ali Hajimiri, a professor of electrical engineering and medical engineering at the university. "There are two worlds today—the physical world and the information world—and anything at the intersection will be a very hot area for the foreseeable future," Hajimiri says.

It's no wonder, then, that popular areas for Caltech's grads include silicon photonics, integrated photonics, lidar, sensing, and actuation. Hajimiri is particularly excited about one nascent field that represents strong opportunity for EEs: wireless power.

"We talk so much about wireless technology, but we are ultimately wired—because when a battery dies, all of the device's fancy functions go out the door until we can plug in," Hajimiri says. Industry players in wireless power include bigwigs like Apple and Samsung, plus startups like Energous, which late last year received Federal Communications Commission approval for a transmitter that powers up devices as far as 3 feet away. (The company is rumored to be working with Apple on long-range wireless iPhone charging.)

It's a tech, tech, tech, tech world, and that holds true across the globe. As a result of this "technology-in-absolutely-everything trend," says Keith Jones, London-based managing director at the recruiting company Talascend, the European automotive and aerospace sectors remain strong, along with robotic products that are focused on boosting efficiency in the medical and manufacturing industries.

With these emerging technologies, recent grads may again have the advantage, as not even engineers long into their careers have specific experience. "Companies figure, if I bring on someone older and more expensive from outside the industry, I have to train them anyway. So why not bring in a cheaper, new graduate and get them up to speed?" Jones says.

The talent gap is particularly significant in the United Kingdom, where 61 percent of businesses "were not confident there will be enough people with the skills to fill their high-skilled job vacancies," according to the 2018 annual report from the nonprofit EngineeringUK. In particular, U.K. engineers have a great opportunity in massive new nuclear power projects, Jones says. These include the £20.3 billion project Hinkley Point C, a Somerset-based plant that is expected to deliver 7 percent of the United Kingdom's power generation capacity.

In Asia, the region has enjoyed years as a dependable hub for lower-cost manufacturing, product, and design talent. But Jones says that trend is starting to cool a bit as companies begin to move some of those functions back in-house in Europe. Production has generally been a bit slower in Asia, but Jones says that as of late, shipyard activity is picking up, thanks to public project awards.
—JULIANNE PEPITONE

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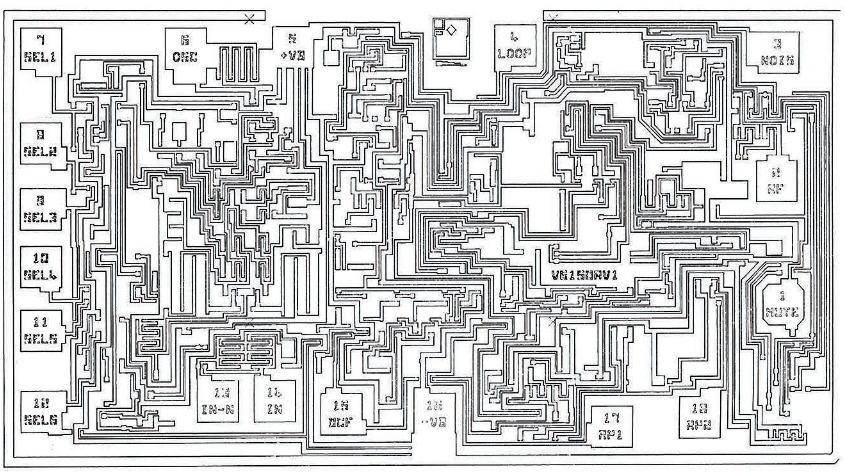
RADIO FREE EVERYWHERE

THIS INDUCTEE INTO THE CHIP HALL OF FAME MADE FM RECEIVERS UBIQUITOUS



***Last year, we inaugurated** IEEE Spectrum's online Chip Hall of Fame, highlighting 27 integrated circuits that helped shape the modern world. This year we add five new inductees, including the Nvidia NV20, a GPU that serendipitously paved the way for the machine-learning revolution, and the Photobit PB-100, the image sensor that put webcams on the map. For the full list and their citations, visit the hall, but as an example of how a tiny device can have a big impact, here's the tale of one inductee, the Philips TDA7000 FM receiver.*

THE RADIO STARS: Dieter Kasperkovitz [left] and Harm van Rumpt squeezed a radio receiver into a microchip, spawning countless gadgets.

FM radio is now a standard feature in a staggering number of gadgets, including alarm clocks, wristwatches, and music players. But before the early 1980s, conventional radio functions were costly and time consuming to build. Manufacturers typically had to make 10 to 14 circuit adjustments, known as alignments, to ensure that reception was good and that the frequency shown on the radio's tuning scale was correct. What changed was the advent of the Philips TDA7000, a chip that made cheap, easy, and ultrasmall FM radio possible.

Working in Philips's Netherlands R&D lab in the mid-1970s, engineers Dieter Kasperkovitz and Harm van Rumpt had managed to fit an entire mono FM receiver, from antenna input to audio signal output, on a 3.5-millimeter-square chip. The only external pieces were an adjustable resonant circuit for tuning the radio to the desired frequency and as few as 14 ceramic capacitors, plus the power supply and speaker. Only one alignment was needed.

Ebullient, the duo patented their creation in 1977 and presented it to the Philips corporate team shortly afterward. The meeting didn't go as hoped, with opposition from the radio-manufacturing group.

"It was rejected, period," van Rumpt explains. "The Philips audio people said it was not possible to do this—they hadn't invented it, so it must be impossible, right?—and so [the TDA7000] was more or less put in a drawer."

That might have been the end for the chip, were it not for a third man: Peter Langendam, an atomic and molecular physicist who was then managing a factory at the Philips components subsidiary Valvo, based in Hamburg.

Langendam believed in the technology so strongly that he went rogue, secretly bringing some sample chips from the Netherlands back to Germany to produce a few demo radios. He sent those radios to Japanese clients who went wild for the technology, signing orders for a million chips.

The risk was enormous, but it worked. With the Japanese market proven, Philips was on board—as was everyone else. Suddenly it was possible to cram FM radios into, well, just about everything: alarms, music players, and even wackadoo novelties like sunglasses. Hey, why not? The TDA7000 and its variants made radio capabilities tiny and inexpensive.

The chip changed the DIY radio world, too, making it vastly easier for hobbyists to build an FM radio from scratch and without the endless futzing with a half-dozen components to get the dang thing to work. To date, over 5 billion TDA7000s and variants have been sold.

The TDA7000 was a hit, but its success had demanded that the members of the team put their jobs at risk. Over time, van Rumpt and Kasperkovitz tired of the corporate hoop-jumping at Philips. In 1998 they teamed up with Langendam and another Philips buddy, Harry Schoonheijm, to create their own "inventor company" for transceiver systems.

The naming decision was easy: They would become ItoM, shorthand for "semiconductor ideas to the market."

Langendam retired from ItoM in 2015, but the other three continue to lead the company in creating new chips. And despite the naysayers of the '70s, the ItoM team looks back on the TDA7000's early days with wistful amusement.

"It was a nice environment in that we had a lot of freedom," van Rumpt says. "We could do crazy things without the need to get budgets and a million teams to sign off on it." Kasperkovitz concurs: "It was, you could say, a good old time." **—JULIANNE PEPITONE**

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/fmchip0718

TOP: HARM VAN RUMPT; BOTTOM: PHILIPS

6 WAYS IoT IS VULNERABLE

CONNECTING PHYSICAL infrastructure to the Internet makes systems vulnerable to new security threats. What keeps executives awake at night varies by industry, but cybersecurity problems are worsening everywhere.

Security officers in manufacturing worry about employees inserting infected USB drives into machines, while hospital administrators fear that malware will wipe out an unpatched MRI machine, or that a hacker will direct an infusion pump to administer a lethal dose of medicine.

Josh Corman, chief security officer at PTC, a computer software firm based in Massachusetts, has codified six reasons why security for the Internet of Things (IoT) is different from–and more difficult to tackle than–traditional IT security.

The first is that the consequences of failure are more dire. We've raised the stakes by connecting more physical systems and facilities to wireless networks. When cars or infusion pumps are hacked, people can die.

Which brings us to Corman's second reason that IoT security is a special challenge: The adversaries are unlike any we've seen before. No longer are they lone hackers trying to make money or cause mischief. Today's adversaries are nation states hacking systems in an all-out cyberwar.

Stuxnet, the virus that brought down Iranian centrifuges in 2010, may be the earliest example. Then in August 2017, a Saudi chemical plant was hit by a hack designed to cause an explosion and disrupt petrochemical manufacturing. Experts believe the attack was state sponsored and intended to send a political message.

Two more of Corman's reasons come from timing and economics. When a firm buys a traditional IT system, it can count on the software company's support for a set amount of time. Only in the last few months have some chipmakers and software vendors offered 7- and 10-year support for IoT products. Some still don't provide any specified support contracts, or they limit the term to 2 or 3 years.

In some cases, that's because the economics don't yet make sense. A connected product that generates a small profit may require years of updates, patches, and security evaluations. In the future, the cost of goods sold may need to include annual security updates and patches.

Corman's fifth reason has to do with the scary reality that many connected devices are built with software, hardware, and firmware that are created by different companies and pieced together at the end. It takes only one weak link to create a vulnerability, so if the company that created the telematics system for a car doesn't update its software, the entire car becomes vulnerable. The IT world has a similar challenge, but through years of working together, manufacturers have agreed on systems to keep everything patched.

Finally, many connected devices live in environments unlike any IT system. In a home, there's no IT manager to push patches to a connected fridge. And in an industrial setting, patching one machine might cause it to stop working with other equipment on the line. Here, the risk of a hack may seem low compared with the risk of stopping a process that produces hundreds of thousands of dollars of revenue a day.

In the IT world, there's an entire industry of life-cycle-management software that tracks patches and rolls back buggy software. In the IoT world, we just aren't there yet. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/iotsecurity0718

ILLUSTRATION BY Mengxin Li

FRITZ GORO/THE LIFE PICTURE COLLECTION/GETTY IMAGES

JULY 1958: KILBY CONCEIVES THE IC

IN 1958, 11 YEARS AFTER BELL LABS reinvented the transistor, it became clear that semiconductors would be able to conquer the electronics market only if they could be greatly miniaturized. There wasn't much progress to be made by hand soldering separate components into circuits, but as is often the case, the solution came just when it was needed. • In July, Jack S. Kilby of Texas Instruments came up with the monolithic idea. His patent application described it as "a novel miniaturized electronic circuit fabricated from a body of semiconductor material containing a diffused *p-n* junction wherein all components of the electronic circuit are completely integrated into the body of semiconductor material." And Kilby stressed that "there is no limit upon the complexity or configuration of circuits which can be made in this manner." • The idea was perfect, but its execution, as depicted in Kilby's February 1959 patent application, was unworkable because the wire connections arched above the wafer's surface. Kilby knew that this wouldn't work, and that is why he added a note about connections to be made in other ways. As an example, he mentioned gold deposited on the thin silicon oxide layer on the wafer's surface. • Unbeknownst to him, a few months later, in January 1959, Robert Noyce, then the director of research at Fairchild Semiconductor Corp., was to jot in his lab notebook an improved version of the very same idea. "It would be desirable to make multiple devices on a single piece of silicon, in order to be able to make interconnections between devices as part of the manufacturing process, and thus reduce size, weight, etc. as well as cost per active element," Noyce wrote. Moreover, the drawing accompanying Noyce's July 1959 patent application contained no flying wires; instead it clearly depicted a planar transistor and "leads in the form of vacuum-deposited or otherwise formed metal strips extending over and adherent to the insulating oxide layer for making electrical connections to and between various regions of the semiconductor body without shorting the junctions."

Noyce's patent was granted in April 1961, Kilby's in July 1964. The litigation went all the way to the Supreme Court, which in 1970 refused to hear the case, upholding a lower court's ruling of Noyce's priority. That decision made no practical difference because in 1966 the two companies had agreed to share their production licenses, and the origins of the integrated circuit became yet another outstanding example of concurrent independent inventions. The basic conceptual idea was identical; both inventors received the National Medal of Science, and both were inducted into the Inventor's Hall of Fame. Noyce lived only to 62, but Kilby survived to share a Nobel Prize for physics in 2000 at the age of 82, five years before his death.

Texas Instruments called the new designs Micrological Elements. They were chosen to control intercontinental ballistic missiles and to help land men on the moon.

Their subsequent progress, captured by the still-enduring Moore's Law, has been one of the defining developments of our time. By 1971, basic integrated circuits had matured into simple microprocessors with thousands of components, then advanced to designs that made personal computing affordable, starting in the mid-1980s. By 2003, the component total had surpassed 100 million, and by 2015 the SPARC architecture had reached 10 billion transistors. That represents an aggregate growth of eight orders of magnitude since 1965, averaging about 37 percent a year, with the number of components on a given area doubling about every two years. Today you can fit a 6-transistor SRAM cell in an area of .027 square micrometers. As Richard Feynman famously said, there's plenty of room at the bottom.

Worldwide, semiconductor sales have reached about US $350 billion a year. That's about 7 million square meters of silicon wafers—about the size of Gibraltar. ■

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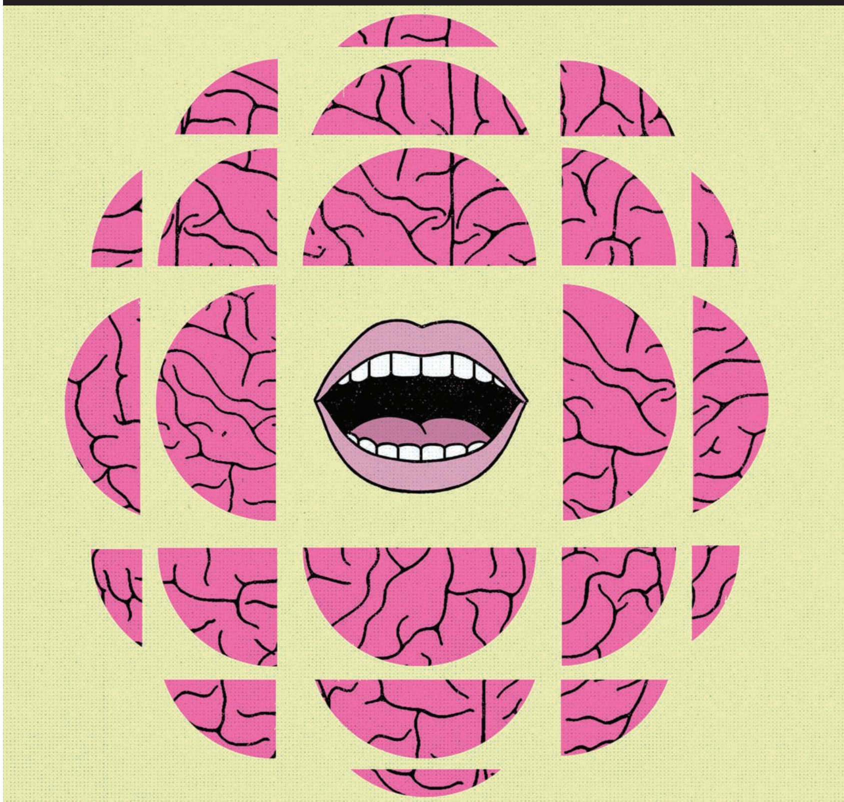

WHEN IMPERFECT UNDERSTANDING IS GOOD

I RECENTLY ATTENDED A CONFERENCE by watching live presentations over the Internet. This was a kind of out-of-body experience, as I virtually hovered over the meeting without the visceral interaction of physical attendance. My attention often wavered, and I viewed the entirety through a sometimes unfocused perspective. • After two days of this, I arrived at an unexpected observation. The talks fell into two distinct categories–those that I understood almost entirely, and those that I hardly understood at all. There were very few in the middle. This got me thinking about the quality and understandability of conference presentations, and how this has changed through the years. • I've attended probably hundreds of conferences. A long time ago the programs were filled with "talks," which were sometimes called "papers." Gradually, "talks" morphed into "presentations." In some settings, the presentations were called "briefings," while at more august events they became "speeches." There are discernible nuances among these descriptions, but in all of them the ultimate aim was ostensibly to inform or educate the audience. • Recalling how conferences were many years ago, I believe that engineers have now greatly improved their ability to inform their listeners. There have been two significant evolutionary forces. PowerPoint caused "talks" to become "presentations," and more recently the advent and general availability of TED talks has set goals for the quality of presentations.

But in thinking about the understandability, I pondered a strange question. As a speaker, what percent of the audience do you *really* want to understand your talk?

Clearly, the answer is not zero, though sometimes there is an urge to impress the audience with your knowledge and accomplishment. I remember attending a board meeting many years ago of a very large and important government defense program. One speaker talked about a technology that might be applied in the program. The talk was way over my head, and I gave up and tuned out. At the end, the speaker asked if there were any questions. Only one hand went up, and the room went expectantly silent, as that hand belonged to one of the most famous physicists in the world. In his characteristic accented whisper, he said, "I have understood...*nothing*...of this." We all realized immediately that this was not a confession but an accusation. Not something you'd want to happen after your own talk!

On the other hand, you might think that the right answer to my question is that *all* of the audience should understand your talk. But maybe not. I think that I often get more out of talks that I don't understand than from those that I do. I may not learn much that's new from those that I understand, whereas some of those that I don't understand leave me feeling that this was an important subject that I need to know more about. In today's world you can learn about anything on the Internet, but time is limited, and the question is what is worth exploring. Just getting a taste of a topic you don't understand can be quite valuable.

If everyone in the audience understands your talk, there is a good chance that a fair fraction of the audience will not learn anything new from it, so maybe you shouldn't want 100 percent of the audience to understand your talk.

The right answer to my question is that 70 percent of the audience should understand your talk. But I just made that up. I have no idea what the answer should be. ■

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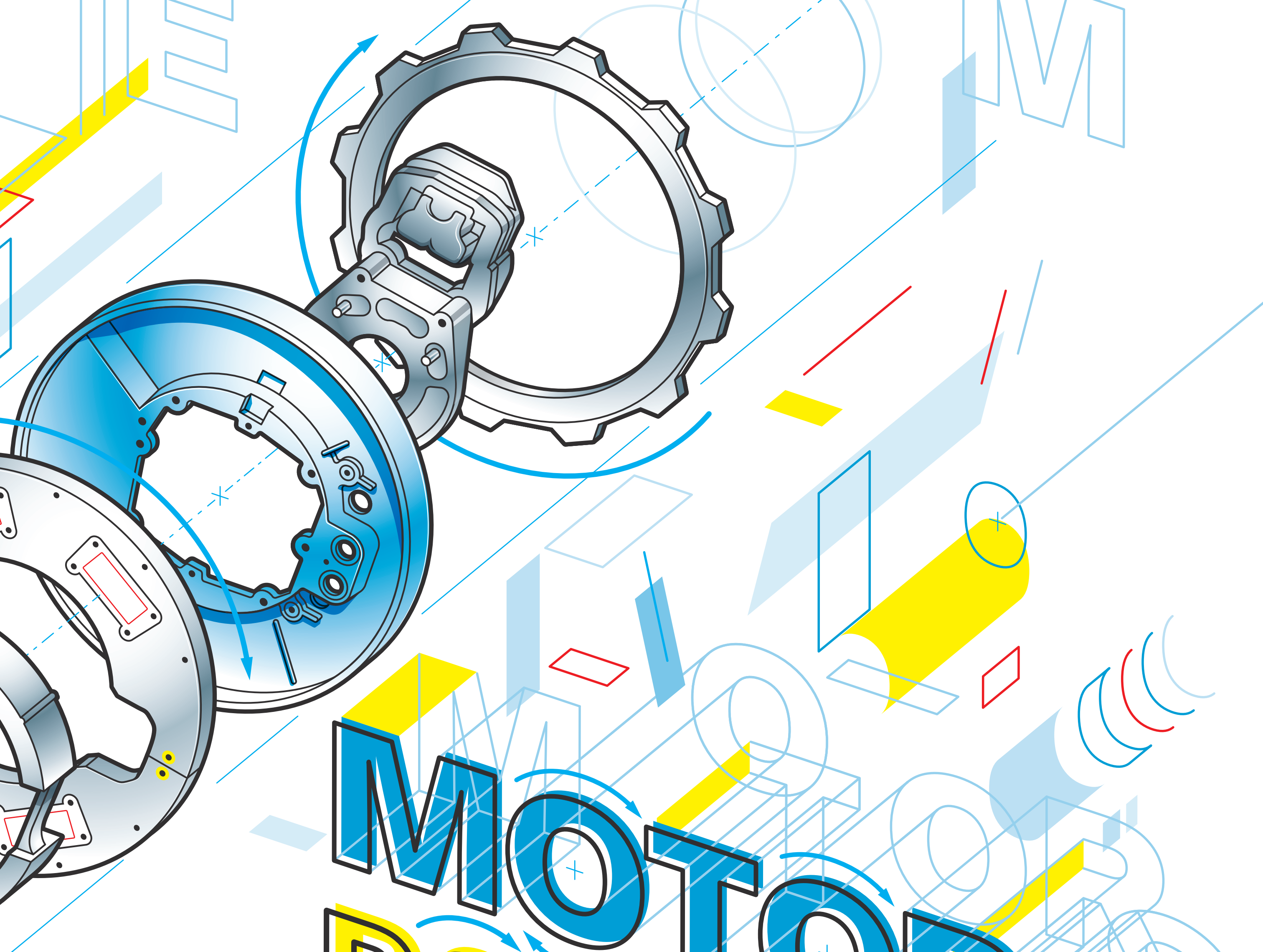
ILLUSTRATION BY Dan Page


IN-WHEEL

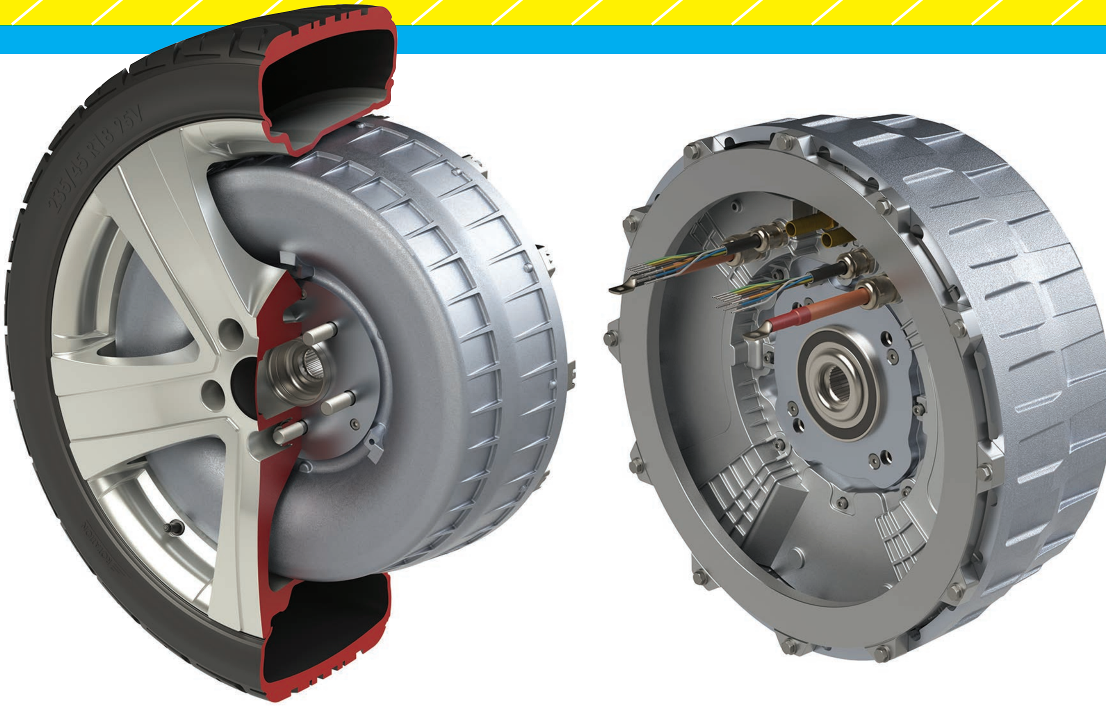


MOTORS ROLL AGAIN

PUTTING ELECTRIC MOTORS CLOSER TO THE ROAD COULD BOOST EFFICIENCY AND IMPROVE HANDLING

BY ANDREW WHITEHEAD & CHRIS HILTON

ILLUSTRATION BY JAMES PROVOST



ALL IN ONE: The Pd18, Protean Electric's flagship product, fits in an 18-inch (46 centimeter) wheel rim. The motor can generate up to 75 kilowatts, or just over 100 horsepower, for each powered wheel. Without any transmission, it can develop torque that is comparable if not better than that of a conventional vehicle. The ProteanDrive system also contains bearings and brakes, so separate components are not needed for those functions.

PROTEAN ELECTRIC

AT THE END of the 19th century, Ferdinand Porsche in Vienna and Joseph Ledwinka and Fred Newman in Chicago attached an electric motor to each wheel of their horseless carriages to provide power simply, efficiently, and controllably. These automotive pioneers hardly expected that electric propulsion would soon wither and that ever more complex hardware would be developed to transform the output from a centrally mounted internal combustion engine into torque at the wheels. But that's what happened.

A century later, though, the desire to reduce greenhouse gas emissions, to be less reliant on fossil fuels, and to clean up the air in our towns and cities has revived interest in vehicle electrification. That interest is particularly strong in China, where the government has declared that some 5 million electric vehicles should be on the road by 2020. That's going to be tough, because many of the country's more than 100 automakers lack the engineering expertise to develop sophisticated electric-vehicle drive systems. Happily, our company, Protean Electric, can serve that market well—with an in-wheel motor that puts the power just where you need it: in the wheels. Doing so simplifies the mechanics, provides more room for passengers and cargo, and improves handling to boot.

With support from investors and partner companies around the world, Protean is building manufacturing facilities in China. Our first factory, located in Tianjin, is currently producing in-wheel motors in low volumes, and we are working with many Chinese automakers to incorporate our technology into their electric and plug-in hybrid vehicles. If all goes as planned, we will see vehicles with our motors on them for sale any minute now. So let us explain in more detail how those motors work and why we think they represent the future of automobile electrification.

ATTACHING MOTORS DIRECTLY to the wheels would seem the obvious way to go, if only for the mechanical simplicity this strategy provides. Yet none of the big manufacturers is doing this with hybrid or battery-electric vehicles. Why not?

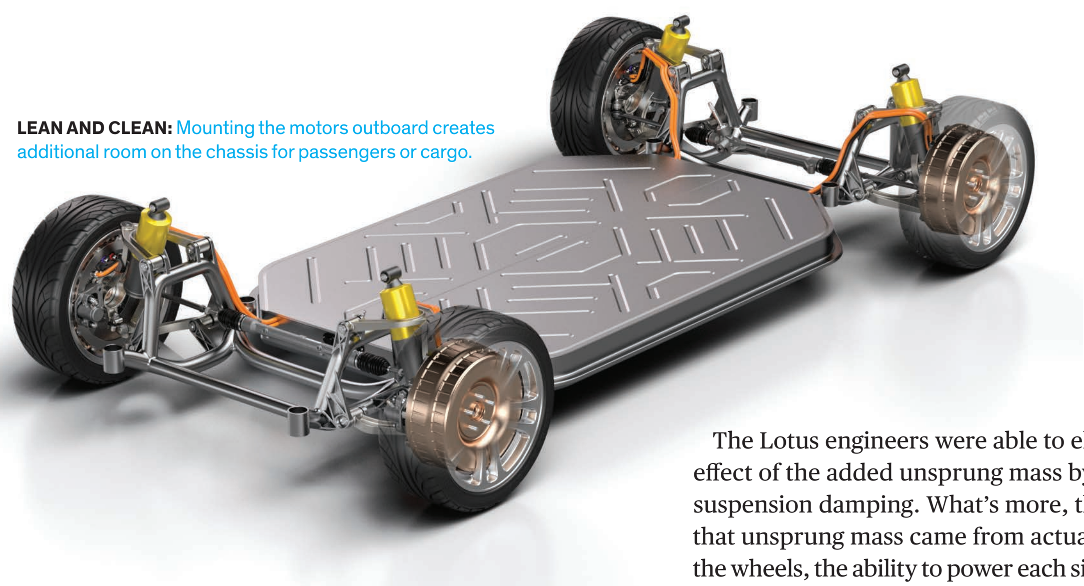
For some manufacturers, the reluctance to adopt in-wheel motors stems from concerns about what is known as unsprung mass. This phrase refers to the mass of everything between a car's suspension system and the road. In a conventional vehicle, this includes brakes, bearings, wheels, constant-velocity joints (the devices on the ends of the drive axles that let them transmit power at an angle), and tires. It doesn't include the rest of the drivetrain, namely the engine or motor and the transmission, which are housed on the vehicle's chassis, typically under the hood.

Keeping unsprung mass to a minimum is a good thing. Reducing it improves ride quality for the driver and passengers and makes it easier for the suspension to keep the tires in contact with the road.

A vehicle powered by in-wheel electric motors will have significantly greater unsprung mass, of course, because the weight of a motor will be carried in each powered wheel. So, many automobile designers consider in-wheel motors to be inherently problematic. But are those concerns really justified?

Very early on, we went to Lotus Engineering, in England, a recognized expert in ride and handling, and asked its engi-

ROOM FOR EIGHT: In April, Protean Electric announced a strategic partnership with LM Industries to provide in-wheel motors for that company's autonomous passenger shuttle, a novel vehicle dubbed "Olli."



LEAN AND CLEAN: Mounting the motors outboard creates additional room on the chassis for passengers or cargo.

TOP: LOCAL MOTORS; BOTTOM: PROTEAN ELECTRIC

neers to investigate objectively the effects of unsprung mass on vehicle handling. For our company, this would be a make-or-break test.

Lotus added a mass of up to 30 kilograms to each of the four wheels of a Ford Focus and instrumented the car to measure vibration and movement. The company supported its work with computer simulations to gain a deeper understanding of the effects of adding both static and rotating mass to the wheels. Further, trained drivers performed standardized assessments to provide additional information about how the added mass affected ride and handling.

Lotus found the effect of the increased unsprung mass, though noticeable to a trained driver, was really not all that significant. The added mass made the car feel as though its suspension and steering hadn't yet undergone the usual tuning activities that are a standard part of vehicle development.

The Lotus engineers were able to eliminate much of the effect of the added unsprung mass by using slightly more suspension damping. What's more, they found that when that unsprung mass came from actual motors attached to the wheels, the ability to power each side of the car independently improved the car's handling substantially.

We've now carried out similar studies on other vehicles. And in all cases, we've found that once the dampers are retuned and we add individual wheel control, the net effect on the vehicle's handling is for the better. So unsprung mass really isn't a showstopper after all.

Another concern about using in-wheel motors has been the added complexity of the software for the motor controller. This software has to make decisions about what torque to demand from each motor at each instant, based on the vehicle's condition and the driver's commands. Under normal circumstances, running two motors instead of just one is straightforward. But if a fault occurs in one motor, the controller needs to prevent a dangerous asymmetry from developing, which would cause the vehicle to be pulled to one side in an uncontrollable way.

Our response to this very important safety issue was to build into our motors two completely independent systems that can detect a fault and equalize torque across two or more motors. Vehicles must meet ISO 26262, a safety standard that calls for proving that a hazardous technical failure will be extraordinarily unlikely. It's an extremely difficult standard to satisfy, but we are confident that our motors will support carmakers in complying with these requirements.

What about cost? No matter how whiz-bang the technology, if it's too expensive customers will shy away. We have compared the cost of a typical electric drivetrain, one with a gearbox, motor, differential, and driveshaft, with the cost of two in-wheel motors. Although two motors are somewhat more expensive than one central motor and drivetrain, the in-wheel system is more efficient because it has a lower mass and doesn't suffer from frictional losses in the transmission. That means that in many cases the carmaker can deliver a vehicle that goes faster or farther (or both) while costing no more than competing models.

Yet another concern that has been voiced about in-wheel motors is their supposed lack of durability. Placing the motors in the wheels, as opposed to under the hood, means they will get battered when the car travels over rough roads. They'll also be pelted by water, sand, gravel, and all the other detritus we drive over on a regular basis. Yes, these conditions could pose a problem, but we've shown through extensive real-world testing that it's perfectly possible to engineer a product that can hold up to the beating.

Such worries have in the past blinded most automakers to the advantages of in-wheel motors. A few have explored them in concept vehicles, and a handful of companies are now trying to bring in-wheel motors, which have long been popular for bicycles and scooters, to the automotive market. Protean Electric leads that pack, having done the engineering necessary to make our in-wheel motors a really attractive way to power an electric vehicle.

OUR NEW IN-WHEEL MOTOR SYSTEM, which we call ProteanDrive, is a complete drivetrain in the wheel. But maybe *drivetrain* isn't the best word to describe it: There are no gears or transmission. Instead, the rotor of the electric motor connects directly to the hub, delivering torque from the motor to the wheel. This results in maximum efficiency and compactness.

While we've designed motors of different sizes for different applications, our flagship product is the Pd18, so named because it is designed to fit in an 18-inch-diameter (about 46-centimeter) wheel rim. The Pd18, which weighs 36 kilograms (79 pounds), can deliver 1,250 newton meters (922 foot-pounds) of torque and 75 kilowatts of power at the wheel. That means two of them could offer up to 2,500 Nm of torque and 150 kW of power.

That might seem an inordinately large amount of oomph, considering that a typical internal-combustion car engine can produce only a few hundred newton meters. But you have to remember that in a conventional car the engine torque is multiplied by whatever the gear ratio is between the engine and the wheels. In first gear, that might be a number like 10; in higher gears the multiplier would be lower. So a pair of Pd18s can match the typical level of wheel torque a conventional car can provide.

NEW AGAIN: A reconstructed version of the turn-of-the-20th-century Lohner-Porsche Semper Vivus with its two in-wheel electric motors in the front goes for a spin in 2011 on Porsche's test track in Weissach, near Stuttgart.

PORSCHE MUSEUM

At the core of our ProteanDrive is a permanent-magnet synchronous motor and a set of tightly integrated electronics. The electronics send precisely controlled currents into the windings of the electromagnets of the motor, creating magnetic fields that interact with the rare-earth permanent magnets affixed to the rotor. By this mechanism, each in-wheel motor can deliver the amount of torque demanded of it in as little as a millisecond.

The electronic circuitry is designed to fit within the overall motor package and shares cooling with the motor, whose windings have up to 90 amperes flowing through them and thus generate a lot of waste heat. That heat, along with the heat from the electronics, is carried off by water flowing through a coolant channel in the motor housing. The coolant is in good thermal contact with both the electronic components and the motor windings. Those windings are encapsulated in a protective epoxy resin, which helps to conduct heat away. That close integration of the motor and drive electronics enables a very small motor to generate a great deal of power.

The software, running on a microprocessor supported by a field-programmable gate array, makes 16,000 decisions per second on what voltages should be applied to the windings, based on measurements from sensors that deliver information on the electrical and thermal condition of the motor as well

as its position and speed. The software ensures that the electrical currents flowing through the motor are exactly right for smooth, quiet operation.

Because the motor requires no transmission or differential or constant-velocity (CV) joints to connect with the wheels, it loses far less energy to friction and thus can use a smaller battery to deliver the same range. That represents a significant savings. It also promises to reduce operating costs, as any car owner who has had to replace a torn CV boot will appreciate.

Space is another advantage. Without a big electric motor under the hood, there's a lot more room in a car for people and things. Placing the motors on the wheels provides designers with greater freedom to develop new vehicle layouts, something our customers are beginning to realize is a huge value.

Handling, though, is where in-wheel motors really shine. Conventional vehicles implement functions like traction and stability control by slowing down the wheel that is spinning faster than it should. But that approach is rather slow to respond and is limited to applying retarding force. To unlock a skidding tire, it would be preferable to apply some driving torque. With in-wheel motors, you can do that. Indeed, you can deliver precisely controlled braking or motoring torque on a millisecond timescale and thereby greatly improve traction and stability control, reducing stopping distances and enhancing drivability and safety.

In-wheel motors also allow for what's called torque vectoring—the application of different torques to different wheels—which can improve handling markedly. Honda, for example, has built its Super Handling All Wheel Drive system into certain vehicles. But the mechanics to achieve that goal are generally complicated and expensive. In a car that uses an in-wheel motor system, this ability comes essentially for free, requiring only the right software. The result can be a vehicle than corners as if on rails, one that can feel both nimble in city traffic and stable at high speeds.

TO ACHIEVE ALL THIS, we've had to overcome some tough technical challenges. One was miniaturizing and integrating the inverter: the electronics that convert direct current from the vehicle's battery into alternating current for the motor. Most inverters for vehicular applications are the size of a large shoebox, but we have packaged ours into less than half that space, so that it can fit neatly behind the electric motor. Packaging things in this way lets us run just two DC cables to each motor, rather than sending AC over as many as six cables, which we would have needed to do had we mounted the inverter elsewhere.

Unlike most of our competitors' products, our motor is configured with the rotor on the outside. This arrangement places the gap between the stator and the rotor (across which the magnetic forces are developed) at the maximum radius available, thereby creating as much torque as possible within the confines of the wheel rim. This approach lets our motor develop sufficient torque without the need for gearing, which would have lowered efficiency and generated noise.

Of course, creating that torque requires substantial amounts of current, and so the windings and electronics can produce a lot of heat. We had to work out a way to get that heat out of the motor to prevent various components from frying themselves. How much heat are we talking about? Well, a single heating element on an electric stove generates around 3 kilowatts, and our motor produces up to 6 kW. We handle this heat with our liquid cooling system, which includes a radiator mounted centrally in the vehicle.

We designed everything to withstand the various environmental conditions a wheel might experience over the lifetime of the vehicle. And it's not just shock, vibration, water, and rocks that we have to anticipate: When the driver demands power from the vehicle, the electronics rapidly become hot and then later cool down; this repeated thermal cycling can lead to premature degradation of the components. So we used special rigs to test the electronics and identify weak points. We now have what we feel is a very robust design, one that will last the lifetime of the vehicle, which we define as 300,000 kilometers, 15 years, and 8,000 operating hours—these being the general expectations of this very demanding industry.

THERE IS ONE CHALLENGE that we have yet to overcome, though: the fixed mind-set of some automakers. Many of them have decided that in-wheel motors aren't practical, and it's been hard to convince them otherwise. That's why we're so excited about our projects with newly established automakers, both in China and the West, which are more open-minded.

Although we've been slower to make inroads with traditional automakers in Europe and North America, we are beginning to gain traction there. We now see strong demand in applications for which in-wheel motors can provide obvious competitive advantages, such as low-floor cargo vehicles and electric all-wheel-drive cars and trucks. Designers of tomorrow's autonomous vehicles are also very interested in the freedom that in-wheel motors can provide.

While we can't be too specific here, we expect our customers and strategic partners will be making some exciting announcements later this year. So we're confident that Protean is poised to finally realize the potential that some of the earliest automotive pioneers envisioned when they built electric motors into their horseless-carriage wheels more than a century ago. ■

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Illustrations by Greg Mably

The Future of Cybersecurity Is Quantum

By Carlos Abellán & Valerio Pruneri

Truly random numbers will provide an unbreakable tool set for cryptography

In 1882, a banker in Sacramento, Calif., named Frank Miller developed an absolutely unbreakable encryption method. Nearly 140 years later, cryptographers have yet to come up with something better.

Miller had learned about cryptography while serving as a military investigator during the U.S. Civil War. Sometime later, he grew interested in telegraphy and especially the challenge of preventing fraud by wire—a problem that was frustrating many bankers at the time. As a contemporary, Robert Slater, the secretary of the French Atlantic Telegraph Co., wrote in his 1870 book *Telegraphic Code, to Ensure Secresy* [sic] *in the Transmission of Telegrams*, "Nothing then is easier for a dishonest cable operator than the commission of a fraud of gigantic extent."

In his own book on telegraphic code, published in 1882, Miller proposed encrypting messages by shifting each letter in the message by a random number of places, resulting in a string of gibberish. For example, to encode the word *HELP*, you might shift the *H* by 5 so that it became an *M*, the *E* by 3 so that it became an *H*, the *L* by 2 so that it became an *N*, and the *P* by 4 so that it became a *T*. Even a meddlesome cable operator wouldn't know what to make of *MHNT* unless he also had the list of random numbers, 5-3-2-4. For truly unbreakable encryption, each string of random numbers would encode only one message before being discarded.

About 35 years after Miller's book, Bell Labs engineer Gilbert S. Vernam and U.S. Army Capt. Joseph Mauborgne came out with essentially the same idea, which they called the one-time pad. And ever since, cryptographers have tried to devise a way to generate and distribute the unique and truly random numbers that the technique requires. That, it turns out, is incredibly hard to do.

So instead, we've relied on less secure encryption methods, with the consequence that attackers who are sufficiently patient and knowledgeable can now crack into any encrypted data they want. And compared with Miller's day, today we have more ways of connecting than the telegraph–through Internet of Things devices, wearable tech, and blockchain-dependent services, to name just a few–and they all need strong encryption. According to the 2017 "Cyber Incident & Breach Trends Report" by the Online Trust Alliance, more than 150,000 businesses and government institutions were the victims of cybercrime last year. In just one of those attacks, on the consumer credit reporting company Equifax, hackers culled the personal information of nearly 148 million customers. "Surprising no one, 2017 marked another 'worst year ever' in personal data breaches and cyber incidents around the world," the report concluded.

Fortunately, researchers have made good progress in recent years in developing technologies that can generate and distribute truly random numbers. By measuring the unpredictable attributes of subatomic particles, these devices can use the rules of quantum mechanics to encrypt messages. And that means we're finally getting close to solving one of cryptography's biggest puzzles and realizing the unbreakable encryption envisioned by Miller so many years ago.

As **any cryptographer knows,** you need three ingredients to make a hackproof encryption method. First, you need an algorithm that converts your message into a string of meaningless characters. Second, you need a way to produce random numbers. And finally, you need the means to deliver the first two ingredients to the intended recipient without anyone else gaining access.

You cannot protect a message with the first ingredient alone, no matter how good the algorithm is. An encrypted message will be completely exposed to anyone who knows the algorithm used to secure it. That's why we combine the algorithm with random numbers. Despite its relatively simple algorithm, the one-time pad becomes unbreakable with the addition of random numbers. To recover the original message, you need to know the specific sequence of random numbers the algorithm used to encrypt the message. Those random numbers are a cryptographic key, which unlocks the content of the encrypted message, but it's useless for deciphering other messages, just as your house key opens your front door but not your neighbor's. Your encryption system is thus only as strong as your cryptographic key is unpredictable.

Unfortunately, most sources of random numbers aren't truly random. These pseudorandom-number generators use algorithms to produce sequences of numbers that look random. But again, if you know the underlying algorithm, they become completely predictable.

We can also generate random numbers by measuring physical processes, like flipping a coin or the interference of radio communications on an electric current. One problem with this approach is that if the process is bound by the laws of classical physics, the measurements can be predicted. To be sure, it may take some doing to reverse engineer what's being measured, but a cryptographer has to assume that somebody will eventually find a way to do so.

Many physical random number sources are also slow. One common method is to record the coordinates of mouse clicks or movements on a computer screen. KeePass, an open-source password manager, uses mouse jiggles to generate a master password. Think how much random clicking or jiggling it would entail just to encrypt every email you wanted to send.

What's needed, then, is a source of true randomness that is fast enough and that any device can use. That's where quantum mechanics comes in.

By their nature, subatomic particles like electrons and photons behave in ways that can't be predicted. If you take two photons emitted by the same atom at different times but under the same conditions, they may exhibit different behaviors, and there's no way to predict those behaviors ahead of time. That's not to say any behavior is possible, but of the outcomes that *are* possible, we can't predict which one we'll get. That unpredictability is crucial for developing a random number generator.

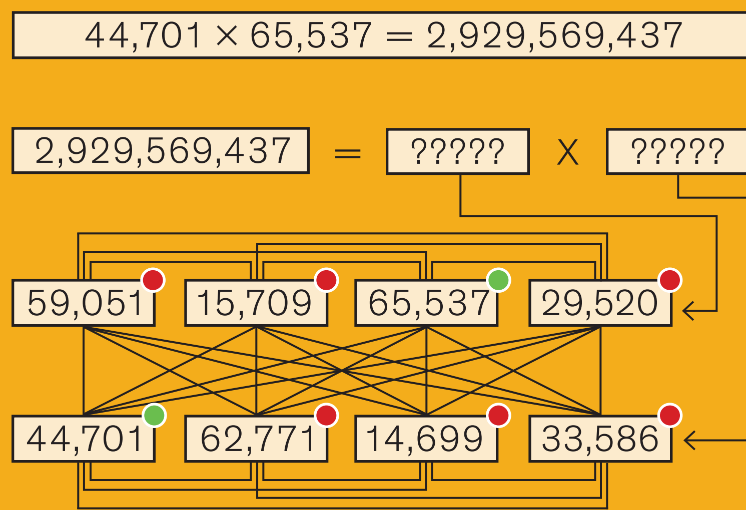
One-Time Pad Encryption

You can't beat one-time pads for security, if you use truly random numbers to shift the letters. Unfortunately, most one-time pads today use algorithms to generate pseudorandom numbers, like this example, which used numbers generated by Google.

H	E	L	L	O		T	H	E	R	E
21	14	21	9	16		23	18	6	1	10
C	S	G	U	E		Q	Z	K	S	O

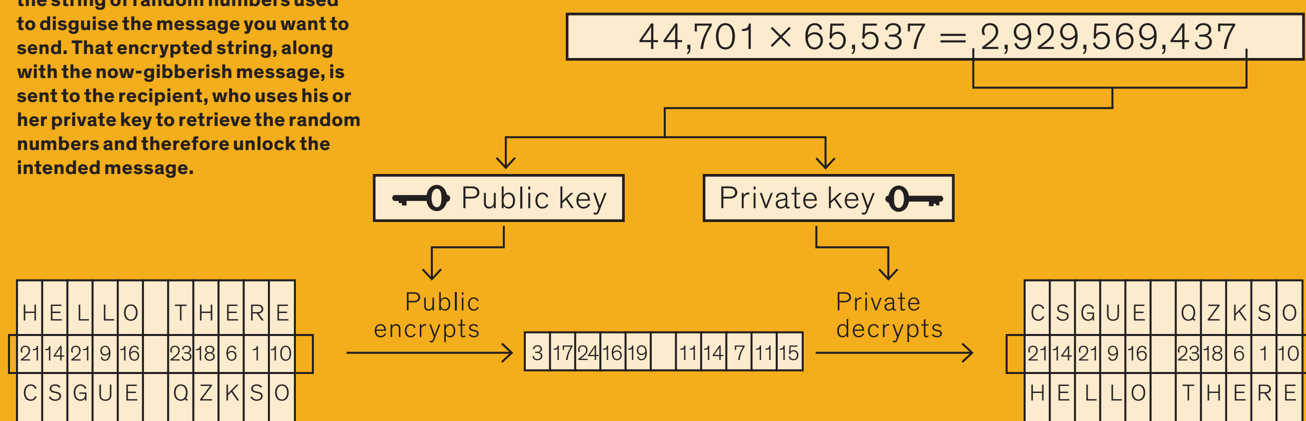
One-Way Functions

The most common example of a one-way function is the multiplication of two large prime numbers (typically thousands of digits long). Any computer can multiply two large primes in the blink of an eye, but even for the fastest, it's very slow going to reverse the process, taking the answer and checking all the possible options until it finds the two initial numbers.



RSA Algorithms

Everything required to keep messages secure comes together with RSA algorithms. After two large prime numbers are multiplied (a one-way function), the result is used to generate two keys for every user on the Internet. One, the public key, encrypts the string of random numbers used to disguise the message you want to send. That encrypted string, along with the now-gibberish message, is sent to the recipient, who uses his or her private key to retrieve the random numbers and therefore unlock the intended message.



In the 1990s, a team at the U.K. Ministry of Defence became the first to propose a way to use quantum mechanics for random number generation. Today, you can buy commercial quantum random number generators from companies like QuintessenceLabs and ID Quantique. QuintessenceLabs' generators are based on quantum tunneling, which occurs when subatomic particles spontaneously pass through a barrier that according to classical physics they shouldn't be able to cross. The ID Quantique generator tracks the distribution of individual photons as they hit a detector.

All of the available commercial generators are limited to specialized applications, such as encrypting classified military data or financial transactions. They're much too large, or too slow, or too expensive for mass market use. Imagine instead having a tiny quantum random number generator installed in your phone, your laptop, or anything else that needs to communicate securely. Creating such cheap, compact, and quick quantum systems has been the focus of our group's research at the Institute of Photonic Sciences, or ICFO, in Barcelona, for the past eight years.

One of the most promising approaches is based on a type of semiconductor laser called a distributed feedback laser diode. We start by oscillating the laser diode above and below its threshold level—that is, the energy level at which the stimulated emission of photons starts. For our laser diodes, the threshold is about 10 milliamperes. Each time the laser exceeds its threshold level, the laser will emit photons with a random phase, which means that the photons will be at an unpredictable point along their wavelength. Those random phases become the basis for the random numbers we use to generate a cryptographic key.

We've already built several devices that have helped confirm the "spooky action at a distance" principle in quantum mechanics, which is the idea that entangled particles can interact with one another instantaneously regardless of distance. Specifically, our devices provided an observer-independent method of verifying that the spooky action could occur, which is important when it comes to proving that the instantaneous interaction is actually occurring. We built those devices using fiber optic cable, and each was about the size of a shoebox.

Now, using standard chip-fabrication techniques, we've integrated the components for our quantum random number source onto an indium phosphide chip measuring less than 2 by 5 millimeters. This chip can be installed directly into a phone or an IoT sensor.

Quside Technologies, a company spun off from our institute last year, is commercializing components using our technology. (One of us, Abellán, is now Quside's CEO.) Quside's latest generation of quantum sources can produce several gigabits of random numbers per second, which means one source should be enough for any current or emerging encryption need. And because they can be made using standard chip-fabrication techniques, it should be easy to manufacture them in large volumes.

What's more, our chips are immune to nearby electronic interference. Generally speaking, any electronic device may be susceptible to thermal or electronic interference. White noise, for example, can interfere with the reception of radio signals. Quantum sources, being so tiny, are especially susceptible, so in most cases, their designers need to pay close attention to eliminate any effects that might corrupt the pure, inherent randomness from the quantum process. Our solution neatly avoids this problem simply because a photon's phase is largely unaffected by electrical currents in the vicinity.

Another good quantum source for random numbers is light-emitting diodes. In 2015, researchers at the Vienna University of Technology demonstrated the first such compact random number generator. It consists of a silicon-based LED that emits photons in the near infrared and a single-photon detector. Its random number generation was linked to when the photons arrive at the detector. The lab prototype generated random numbers at a rate of a few megabits per second.

A year later, our group in Barcelona demonstrated the chip-based quantum source we mentioned before, that is capable of producing gigabits of random numbers per second using distributed feedback lasers. As a bonus, our sources are built from off-the-shelf components and rely on standard optical communication and manufacturing techniques.

Meanwhile, researchers at SK Telecom, one of the largest telecom providers in South Korea, have demonstrated a random number generator chip that uses a smartphone camera to detect the fluctuations in an LED's light intensity. The design was based on a patent from ID Quantique. The prototype, unveiled in 2016, measured 5 by 5 mm; since then SK Telecom has announced plans for a commercial version that's about the same size—that is, small enough to fit inside your smartphone.

Other researchers are investigating quantum random number generators based on single-photon detection arrays. The arrays can detect the small variations as a light source fluctuates and should provide even better detection of quantum fluctuations than a traditional camera can.

Having an encryption algorithm paired with truly random numbers isn't enough. You still need a secure way to send your message along with the cryptographic key to the recipient.

For encrypting and decrypting keys, the standard protocol for many years has been the RSA algorithm. Developed in 1977 by cryptographers Ron Rivest and Adi Shamir and computer scientist Leonard Adleman, it hinges on a mathematical trick known as a one-way function—that's any calculation that is very easy to solve in one direction but extremely hard to solve in reverse. A classic example—and the one that Rivest, Shamir, and Adleman used—is to multiply two large prime numbers, typically 1,024 or even 2,048 bits in length. It's of course very easy to multiply the numbers together, but it's very hard to factor the result back to the original prime numbers.

RSA and similar algorithms give every network user two keys: a public key (known to everyone) and a private key (known only to the user). To send information, you encrypt it using the recipient's public key. The recipient then decrypts the information using her private key. The algorithms have worked remarkably well for more than four decades because it's extremely hard to crack the private key, even knowing the public key.

The algorithms aren't perfect, however. One of the main problems is that they take a long time to encrypt and decrypt a relatively small amount of data. For that reason, we use these algorithms to encrypt keys but not messages. The other big problem is that the algorithms are crackable, at least in theory. Right now, the only methods to crack the code take too long, provided a mathematical breakthrough doesn't make RSA and similar algorithms easily solvable. For any practical attack, not even today's supercomputers are up to the task.

Using a clever 20-year-old algorithm, a quantum computer, however, could easily calculate prime number factors by exploiting the quantum property of superposition to drastically decrease the computation time needed to find the correct factors. Today's quantum computers aren't powerful enough to handle an RSA-level hack. But it's only a matter of time, and when that day comes, our current cybersecurity infrastructure will become obsolete.

Ideally, we should be able to exchange cryptographic keys that cannot be cracked *before* quantum computers or mathematical breakthroughs catch us by surprise. One possibility is to use a technology called quantum key distribution. Much like generating truly random numbers, quantum key distribution relies on the unpredictable nature of quantum mechanics, in this case to distribute unique keys between two users without any third party being able to listen in. One of the most common methods is to encode the cryptographic key into the orientation of a photon and send that photon to the other person. To achieve full security, we need to combine quantum key distribution with one-time pads to encrypt our messages, which will still require extremely fast random number generators.

We believe these quantum random number generators will be able to provide all the random numbers we'll ever need. We'll also have to continually check that our quantum sources are free from defect and interference and are producing numbers that are truly random. At our lab, we've developed a method for determining how confident we can be in a source's true randomness. Our "randomness metrology" begins with establishing both the physical process that the source uses and the precision of the source's measurements. We can use that information to set a boundary on how much of the randomness is arising purely from the quantum process.

Now that we've taken the first steps in developing quantum random number generators that are small enough, cheap enough, and fast enough for widespread, everyday use, the next step will be to install and test them in computers, smartphones, and IoT devices. With true random number generators, we can produce unpredictable cryptographic keys, and if we combine those keys with a secure method to distribute them, no longer will we have to worry about the computational or mathematical skills of an enemy—even the most capable attacker is powerless against true unpredictability. Nearly a century and a half after Frank Miller proposed his one-time pad, unbreakable security could finally be within our grasp. ■

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THE NIXIE TUBE STORY

By JENS BOOS

The neon display tech that engineers can't quit

NIXIES REBORN: This clock features modern-day Nixie tubes made by Dalibor Farny. The Czech engineer has revived the manufacture of the distinctive display devices, which had their heyday in the late 1950s and 1960s.

ON A COLD DECEMBER MORNING in the Czech village of Březolupy, a man stops his truck in front of a 17th-century castle. He puts on some heavy gloves, steps out of the truck, and opens the back hatch. Carefully, almost lovingly, he unloads crate after crate of heavy equipment and supplies–an industrial glass lathe, a turbomolecular vacuum pump, and glass. Lots and lots of glass.

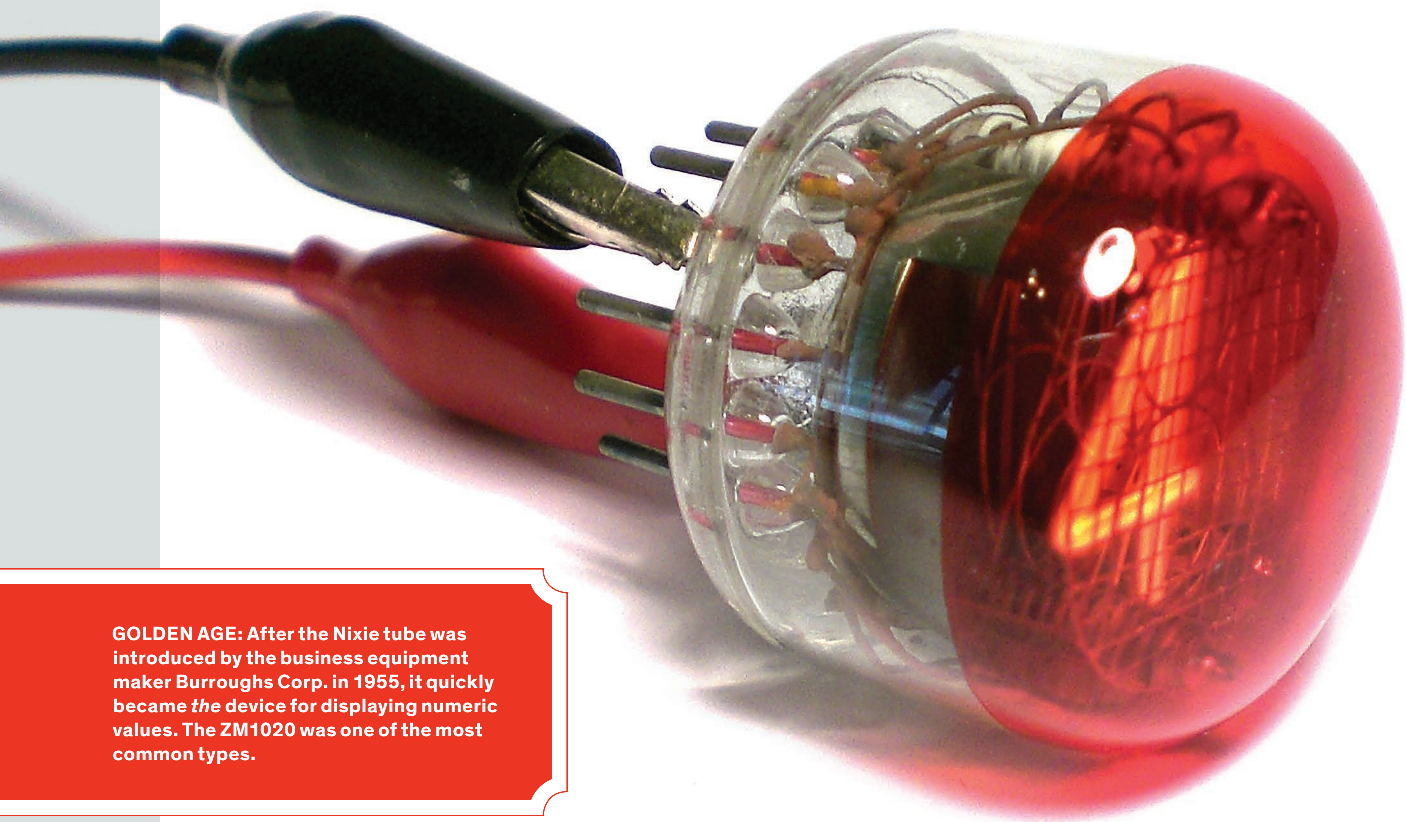
The man is Dalibor Farny. In 2012, Farny began working to revive the manufacture of a display technology called the Nixie tube, the last commercial examples of which were produced when he was still a child.

These neon-filled glow lamps were ubiquitous in the late 1950s and 1960s, illuminating numbers, letters, and symbols in scientific and industrial instrumentation. Born in the basement of a German-American tinkerer in the 1930s and later commercialized by the business equipment maker Burroughs Corp., Nixies displayed data vital to NASA's landing on the moon, lit up critical metrics for controlling nuclear power plants, and indicated the rise and fall of share prices on Wall Street stock exchanges, among thousands of uses. For many people, the warm glow of the Nixie came to evoke an era of unprecedented scientific and engineering achievement, of exciting and tangible discoveries, and of seemingly limitless progress. Remarkably, it continues to do so, even for people who, like Farny, grew up long after the tubes had faded from common use.

In the 1970s, Nixies were eclipsed by LEDs, which were not only much cheaper to make and use but also more versatile. The tubes might have died the lonely death of countless other obsolete devices–and yet they did not. Some Nixies lingered on in legacy equipment, of course. But their extraordinary resurgence didn't really begin until around 2000, when a small but devoted cadre of hobbyists, collectors, and aficionados began searching out and buying old, never-used tubes and designing clocks around them. Nearly two decades later, the movement is still going strong, and Nixies now inhabit a unique niche as ultracool retro tech aimed at discriminating consumers.

We may never fully understand why this quirky technology, out of innumerable others, has been plucked from obsolescent obscurity. But some glimmers, at least, of its enduring appeal emerge from the tubes' colorful history. It's a classic story of 20th-century innovation, complete with a quirky genius, shrewd corporate maneuvering, and brilliant flashes of insight.

THE NIXIE TUBE may seem like an unnecessarily complicated invention for something as straightforward as displaying a number. But if you think about what was technologically possible in the middle of the 20th century, you soon realize it was the most logical and



GOLDEN AGE: After the Nixie tube was introduced by the business equipment maker Burroughs Corp. in 1955, it quickly became *the* device for displaying numeric values. The ZM1020 was one of the most common types.

PREVIOUS PAGES: DALIBOR FARNY

reliable option available. It was also the culmination of a long line of breakthroughs.

Nixie tubes operate through a process called gas discharge. This phenomenon occurs when electrically charged particles, typically electrons, move through a gas at a high velocity—roughly 2 percent of the speed of light. The speeding particles collide with the gas atoms or molecules, ionizing them and creating an energetic plasma of charged ions and electrons. The ions, excited to higher energy states, shed the excess energy as photons of light. The same basic process produces the glow of neon signs and the northern and southern lights. The color of the light depends on the gas: Neon ions emit a red-orange light; hydrogen emits bluish purple; nitrogen gives a spectacular purple; and krypton glows whitish blue.

ALSO-RAN: Among the companies vying to introduce numeric display devices was National Union Radio Corp., but its GI-21 Inditron tube [above] couldn't compete with the Nixie.

The earliest application of gas discharge was the Geissler tube, invented by the German physicist Heinrich Geissler in 1857. The tube consisted of a simple glass bulb with an electric terminal on each end. Air was evacuated from the bulb, which was then filled with neon, argon, or some other gas; some tubes were filled with conducting fluids, minerals, or metals. Applying a direct current of a few thousand volts ionized the gas and caused it to emit light. Scientists used Geissler tubes to understand the nature of electricity, and they were sold as decorative curiosities. The tubes also served as a milestone on the way to the invention of the neon sign, in 1910, and decades after that, the Nixie.

In the late 1920s and early 1930s, inventors realized that the Geissler tube's discharge glow could be extended to the cathode and that you could shape the cathode to confine the glow. By using an appropriately bent wire as the cathode, for example, you could display numbers or text. One of the earliest patents for such a design went to the German inventors Hermann Pressler and Hans Richter (U.S. Patent No. 2,138,197), for what they called an "electric discharge lamp" that functioned as a "self-luminous sign." As the duo noted in their patent, awarded in 1938, their lamp was more readable than a traditional neon sign and would be cheaper to manufacture, because you wouldn't have to bend glass tubes into the form of letters or numbers.

On the other hand, you needed a glass enclosure to contain the gas and provide an envelope for the wires spelling out your message, which would limit the size of your display. For a large illuminated advertisement in, say, New York City's Times Square, Pressler and Richter's technique was simply impractical. No surprise then that the invention didn't find many takers. Today, just a few small versions are in the hands of collectors.

Another inventor, though, had a better idea. Hans P. Boswau, a German immigrant who'd settled in the Lake Erie shore town of Lorain, Ohio, worked as chief engineer at the Lorain County Radio Corp. Through his job, he would have been familiar with many of the latest technological developments of his day. At some point, Boswau decided that he needed a device to display numeric symbols and letters. On 9 May 1934, he filed two U.S. patent applications—No. 2,142,106 and No. 2,268,441—which contain the first complete descriptions of what later came to be called the Nixie tube.

Boswau's key innovation was to stack the cathodes behind one another within the same tube so that the cathodes could be illuminated individually. You could thus configure a single tube with 10 cathodes representing the numerals from 0 to 9. Interestingly, Boswau's patents were issued to him and not to his employer, so he probably hadn't intended them for use on the job. In 2009, a Canadian Nixie tube enthusiast named Randall Logan tracked down Boswau's daughter, then 83, who told him that her father may have constructed primitive versions of his "glow indicator" in his basement workshop. But it appears that Boswau, who died in 1971, never tried to commercialize his indicators, and they likely never left the basement.

SURROUNDED AS WE ARE with electronic gadgets bearing digital readouts, it's hard to imagine a time when numeric displays were virtually nonexistent. In an analog world, though, you didn't really need them. When Boswau was inventing his tube, most circuit indicators took the form of lightbulbs or analog panel meters.

Then came the transistor in 1947 and the rise of digital electronics. Now you could reliably define discrete device states without the use of mechanical switches and perform rapid calculations without the use of room-size computers.

With all those calculations came lots of numbers, which of course you'd want to display. But none of the existing technologies was quite up to the task. In particular, no display could withstand the strong vibrations, broad temperature ranges, and other demands of space exploration and the latest generation of jet aviation. Clearly, a better numeric indicator was needed.

Several companies rose to the challenge. The first post-Boswau patents for a numerical display tube were filed by Northrop Aircraft in June 1950. I've found no evidence that the company seriously developed them, however, nor have any Northrop tubes surfaced in recent times.

A more successful contender emerged in May 1954, when National Union Radio Corp., a well-known manufacturer of vacuum tubes, unveiled its line of neon-filled indicator tubes. Called the Inditron, the device resulted from "four years of research and development [and] two years of pilot production," according to an advertisement.

Much like Boswau's earlier invention, the Inditron consisted of a small glass bulb containing a stack of hand-bent numerals that were electrically isolated from one another. Contacts from each numeral fed through a glass seal to the outside of the tube, where they connected to a power supply.

THIS SPREAD: JENS BOOS (2)

The numerals served as the cathode, but there was no fixed anode. Instead, the numbers that weren't in use functioned as the anode. Let's say you were displaying a 7. External circuitry would connect that number to the negative terminal, while numbers 0, 1, 2, 3, 4, 5, 6, 8, and 9 would connect to the positive terminal. Needless to say, the circuitry required to continuously reconfigure the anode was complicated.

Meanwhile, engineers at Ericsson Telephones, in England, were developing a simple display tube, for which they received a British patent in 1951. Rather than having separate wires for each numeral like the Inditron, the tube illuminated connecting segments to form each number, much like the seven-segment numbers that are common today in microwave ovens and digital watches. Later, in 1958, Ericsson filed for a patent for a more refined numeric indicator, but it came too late. By then the reign of the Nixie had begun.

LIKE THESE OTHER COMPANIES, Burroughs, a major manufacturer of calculators, computers, and other business equipment headquartered in Plymouth, Mich., was also keen on numeric displays. But it lacked the in-house expertise to develop them, and so the company went out and bought the requisite know-how. In 1954, Burroughs acquired Haydu Brothers, a vacuum-tube manufacturer in Plainfield, N.J., known for its high-precision manufacturing capabilities. It also recruited the engineer Saul Kuchinsky, a former employee of National Union Radio who'd worked on the Inditron, to lead a lab at the Burroughs Research Center in Paoli, Pa. Those two moves gave Burroughs everything it needed to develop a numeric indicator tube.

Haydu Brothers had been founded in 1936 by two Hungarian-American brothers, George and Zoltan Haydu, and their father, John Haydu. It quickly gained a reputation for making precision metal parts used in constructing vacuum tubes. Burroughs wanted Haydu to manufacture its high-precision tubes, particularly its line of beam-switching tubes, trademarked as the Trochotron.

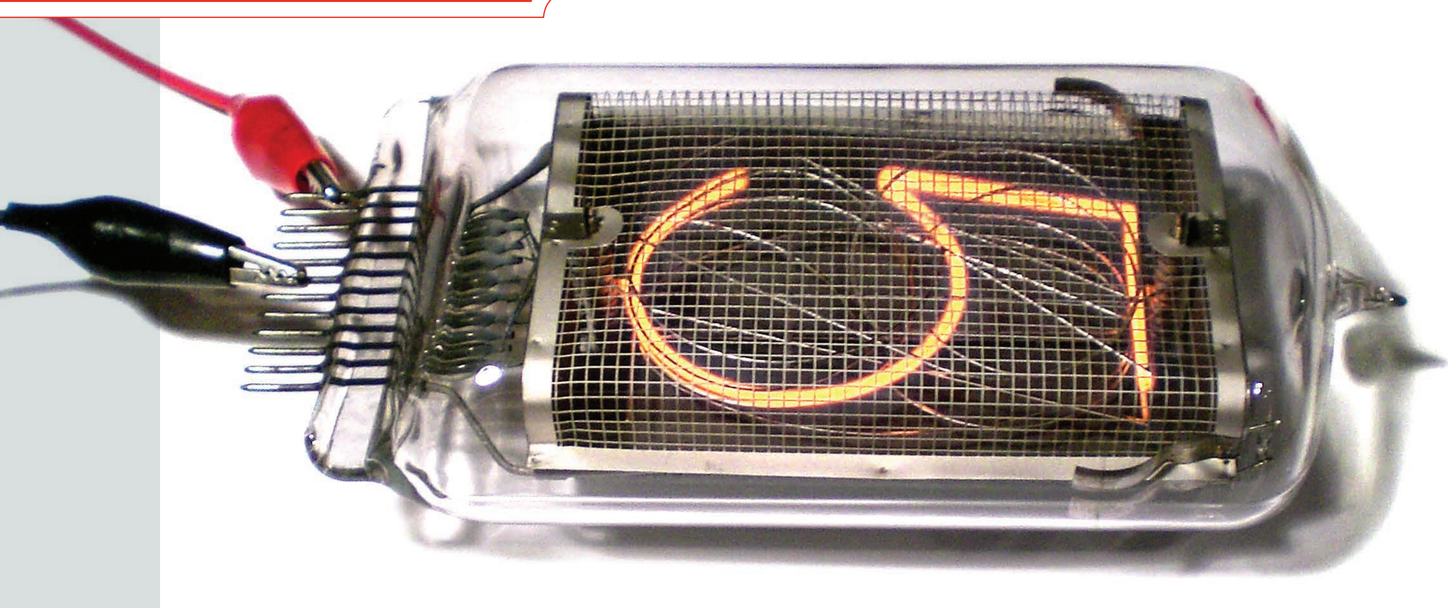
Beam-switching tubes were primarily used as high-speed counters, but they weren't able to display the count. For that, Kuchinsky had to construct a new device, and he drew on his experience at National Union. The Paoli team got to work on a display tube that was similar to the Inditron but much improved. Meanwhile, Kuchinsky also served as general manager of the former Haydu plant in New Jersey, where he could oversee the prototyping of the Paoli lab's devices.

In a 2011 email to me, Roger Wolfe, a Burroughs engineer, recalled the team's first fragile attempt: "We put the tube on life test overnight. When we came in the next day, so much cathode material had sputtered onto the dome of the tube that the numerals were no longer visible. We had invented a tube with a 24-hour life!"

After some tinkering, Wolfe wrote, they discovered that the addition of mercury vapor would greatly extend the tube's life span. The sputtering had been caused by the accelerated neon ions striking the cathode. But when the neon ions collided with the heavier mercury molecules, their energy dropped below the point where they could damage the cathode.

"We secured a tiny ampule with mercury sealed inside, wrapped a few turns of resistance wire around the ampule,

BIG & BEAUTIFUL: The F9020AA Nixie tube was manufactured in France starting in 1962 and used in high-end clocks. At their peak, hundreds of types of Nixies were made by more than two dozen companies worldwide.



JENS BOOS

NAME RECOGNITION: Burroughs Corp. engineer Saul Kuchinsky gave the company's numeric indicators the name "Nixie" because he believed successful brand names often had an *x* in them.

[and] connected the ends of the wire to two of the [tube's] pins," Wolfe wrote. The tube was then sealed, and the team ran current through the wire, which heated and broke the ampule, releasing the mercury.

In August 1955, Burroughs unveiled its new indicator tube at Wescon—the Western Electronic Show and Convention, in California—which was for many years the leading U.S. electronics event. Soon after, it began shipping the first tubes to customers. That December, the company filed for a patent on its "glow indicating tube." The devices were mechanically superior to the numeric display tubes still on offer from National Union: They had dedicated anodes made from wire mesh, and instead of hand-bent wires, the cathode numerals were etched out of thin sheet metal. The addition of mercury prolonged the tubes' life span, eventually to more than 200,000 hours.

The tubes by then had also acquired their distinctive name. Lore has it that Kuchinsky's first concept drawing for the indicator tube was labeled "Numerical Indicator Experiment No. 1," which was shortened to NIX1. Wolfe told me that "besides being an engineer, Kuchinsky had a flair for marketing and believed that successful brand names often had a *k* or an *x* in them (e.g., Kodak, Xerox, etc.). Hence 'Nixie' fit right in with his belief."

It seems only fair that the man behind the tube also got to name it. Jay Scovronek, a reliability manager who worked with Kuchinsky, describes him as "a modest guy who likes to give credit to people for their contributions. But Saul was the driving force that brought the Nixie to life."

COMPANIES IN THE UNITED STATES and abroad rushed to license the Nixie technology from Burroughs, which also supplied the tubes as OEM products that could be integrated into other companies' systems. The tubes quickly became *the* device for displaying numeric values in multimeters, counters, and other scientific and industrial equipment. A remarkable variety of tubes emerged, ranging from miniature versions for tabletop instruments to large tubes with 13-centimeter-tall digits that could be read from afar. Throughout the 1960s, over two dozen companies in the United States, Europe, the Soviet Union, India, China, and Japan were making and supplying Nixies.

This period, from 1955 through the 1960s, was the golden age of the Nixie, but its replacement was already in the works. In 1962, Nick Holonyak Jr., working at the General Electric Laboratories in Syracuse, N.Y., managed to control the electroluminescence of a mixed crystal of gallium arsenide phosphide, and the light-emitting diode was born. But it would take some years to turn the device into a sellable product.

Meanwhile, Nixie sales were booming. As late as 1971, an editorial note in *Electronic Buyers' News* predicted that "LEDs may follow the historical pattern and become another 'also ran'" and declared "Nixie tubes are here to stay."

This juxtaposition of the LED as the upstart technology challenging the incumbent Nixie may strike you as funny, but that's because you know how the story ends. What you might *not* know is that the first commercial LEDs were not nearly as bright and reliable as today's. Engineers continued to extend the devices' life span while boosting their efficiency and brightness and expanding their range of colors and applications. With the rise of digital integrated circuits, it made more sense to use low-voltage readout devices like the LED rather than the high-voltage Nixie tube, which typically required 200 volts or more to ionize the neon and get a nice, bright glow. Slowly but steadily, Nixies faded from view. The Soviet Union was the last country in which the tubes were continuously manufactured, into the early 1990s.

OUR STORY MIGHT HAVE ENDED there but for the rise of another, far bigger invention: the World Wide Web. Very quickly, the Internet enabled Nixie tube fans from all over to connect and share ideas, pictures, and videos of their projects. The main virtual meeting ground became the Yahoo group Neonixie-l, which a decade later migrated to the Google group of the same name. A steady supply of Nixie tubes and supporting electronics began popping up on online auction and electronics websites. Occasionally, younger people who'd never encountered a Nixie in the wild would stumble upon the group and become mesmerized by the vivid images of the strangely glowing displays. Vintage Nixie tubes began to surface in consumer products, such as clocks, chessboards, and even wristwatches.

By now you may be wondering: If Nixie tubes are no longer being widely manufactured, won't they disappear completely at some point?

It's true that the most common types of vintage Nixies are still available, but their prices in many cases have risen by a factor of 10 or 20 in the last decade or two. The largest Nixie tube, the CD47, now sells for around US $1,000; back in 2000, it could be had for $100 or less. Some individuals, spotting an opportunity and a challenge, set out to make their own artisanal Nixie tubes. These new Nixie pioneers include Aleksander Zawada in Poland, Ron Soyland in the United States, and the aforementioned Dalibor Farny. A YouTube video of Farny demonstrating his Nixie process has garnered 1.3 million views. Farny makes his tubes in small batches and sells them for a profit, thus ensuring that a bygone technology remains in view.

In the now-prophetic words of that 1971 editorial: Nixie tubes are here to stay. ■

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/nixietubehistory0718

HAYDU BROTHERS/JENS BOOS


When E-Cigarettes Go...

Boom

The most immediate threat from these nicotine-delivery devices is exploding batteries

By **MICHAEL PECHT**

Photograph by **THE VOORHES**

On 23 November 2016, as he stood behind the counter of a wine store in New York City, Otis Gooding felt an explosion on his right thigh. The e-cigarette he'd been carrying in his pants pocket had suddenly erupted like a small fireworks display. As a security camera later showed, the 31-year-old Gooding struggled to pull the burning device out of his pants. Gooding would later need a skin graft and 51 staples, and he may never recover the full use of his hand.

Exploding cigarettes sound like a party joke, but today's version isn't funny at all. In fact, they are a growing danger to public health. Aside from mobile phones, no other electrical device is so commonly carried close to the body. And, like cellphones, e-cigarettes pack substantial battery power. So far, most of the safety concerns regarding this device have centered on the physiological effects of nicotine and of the other heated, aerosolized constituents of the vapor that carries nicotine into the lungs. That focus now needs to be widened to include the threat of thermal runaway in the batteries, especially the lithium-ion variety.

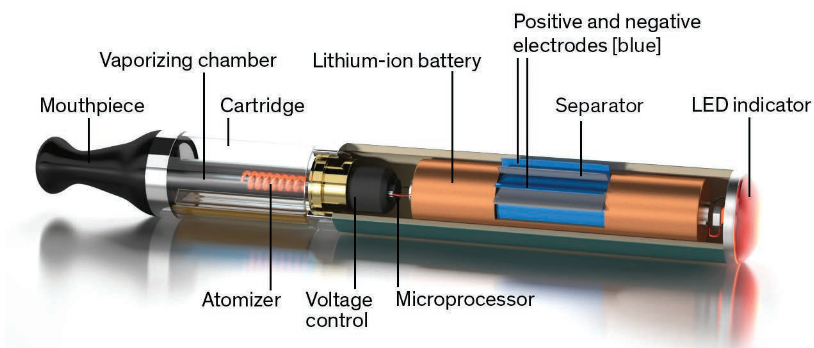
In July 2017, the National Fire Data Center of the U.S. Fire Administration identified 195 separate e-cigarette incidents in the United States between January 2009 and 31 December 2016. Thirty-eight incidents resulted in third-degree burns, facial injuries, or the loss of a body part. The number of fires and explosions has risen in tandem with the rise in e-cigarette sales. The report also notes the lack of regulations, codes, or laws governing the safety of the batteries in e-cigarettes. And there's reason to believe that many cases of injury are never registered with government authorities. An online blog asserts that at least 243 e-cigarette explosions occurred from August 2009 to April 2017, resulting in 158 personal injuries. Other explosions harmed animals or property.

E-cigarettes, also known as "vape pens," "e-hookahs," "mods," "e-pipes," "cigalikes," and "tank systems," are basically just electronic nicotine-delivery systems. They were first commercialized in China in 2004, and the most recent available estimate put that country's share of total production above 90 percent. In 2015, U.S. consumers accounted for about 43 percent of the US $8 billion world market for these devices.

An e-cigarette typically consists of a cartridge containing a liquid, an atomizer based on a heating element, and a battery that powers the heating element. When the user inhales, the airflow activates a flow trigger, and the heating element vaporizes the liquid—a solution of propylene glycol, glycerin, flavoring, and varying levels of nicotine.

Lithium-ion batteries are suitable for e-cigarettes because they are rechargeable and have high levels of energy density and voltage. But under certain conditions, the battery can fail spectacularly through a process known as thermal runaway. In this situation, internal defects cause short circuits, which raise the temperature enough to spur on reactions that release still more heat. Ultimately, this feedback loop leads to sparking, fiery self-destruction. Significantly, this phenomenon is more likely in an e-cigarette than in a cellphone because the combination of lithium-ion batteries with a heating element increases the risk of such a reaction. A battery-management system can help with the problem, but it may not prevent catastrophic failure if poor manufacturing and quality control leave defects in the battery.

During thermal runaway, battery temperatures can reach 900 °C and release flammable and toxic gases. Well-known examples of thermal runaway include the various battery fires that led to the worldwide grounding of the Boeing 787 Dreamliner aircraft on 16 January 2013; other notable incidents involved hoverboards and Samsung's Galaxy Note 7 smartphone.



IN YOUR FACE: This cutaway illustration of an e-cigarette is technically known as a transparency; an exploded view would show it with the components pulled well apart.

The way to stop the problem is by ensuring high manufacturing quality. Many of the batteries included in e-cigarettes have an excessively high rate of internal defects. These include foreign matter (dust, contaminants, even moisture) and poorly formed electrodes or separator—the membrane that prevents short circuits by keeping the electrodes apart while allowing the passage of ions during charging or discharging. Low-quality machining can result in small metal protrusions, or it can cover the electrodes in unwanted metallic particles. These flaws can also lead to short circuits in the battery. For instance, the electrode can have burrs that can tear the separator. If the separator is penetrated by a wayward particle or if for some other reason a hole should form in it, enabling the anode and cathode to touch, a short circuit can ensue.

Another concern is the very construction of the batteries. Cellphones and portable computers normally use pouch cells, which are contained in a plastic wrap. But e-cigarettes typically use batteries that are shaped like cylinders and encased in a metal can (which is preferred to softer wraps made of plastic because it's easier to handle and more rugged). To understand why this can be a problem, consider that during normal operation, Li-ion batteries release small amounts of gas, mostly carbon dioxide. This gas release can be contained within the can without swelling. However, during thermal runaway, gases (including toxic fluoride gases) are generated in such quanti-

ILLUSTRATION BY Jean-Luc Fortier

ties and at such speed that the pressure can easily build up, turning the battery into a pipe bomb.

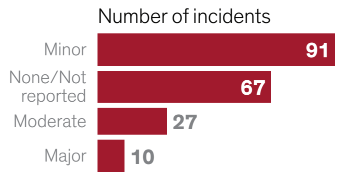
And in fact many of the people wounded by e-cigarette malfunctions suffer not so much from the heat released as from the sheer force of the explosion. One man from Orange County, Calif., lost an eye. Another man, in Bakersfield, Calif., suffered injuries to his mouth and teeth. Still others have had holes blown through their cheeks.

Some companies have installed vents, similar to those in a pressure cooker, to allow gases to escape. Even so, this release mechanism is usually not sufficient to release the gases if the thermal runaway occurs at a fast pace.

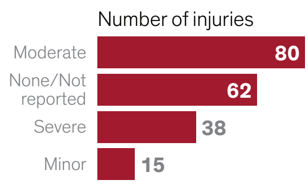
It costs money, of course, to maintain high manufacturing standards. It's not hard to see how the drive to cut costs has created incentives to use defective and substandard batteries. Such batteries enter the supply chain by different routes.

Some of the batteries may have originally been made by reputable manufacturers who identified them as substandard and labeled them as such, intending that they be used only in applications for which fire is not a pressing problem. Or maybe the batteries were meant for recycling but ended up in the hands of unscrupulous suppliers, which often rewrap low-grade batteries. That is, they put a new label on the batteries and sell them under a different company name, sometimes with exaggerated ratings and occasionally at a higher price than batteries from the original manufacturers. Typically, there is no way to identify the original manufacturer.

Fire Spread in E-Cigarette Fire and Explosion Incidents



Injuries Reported in E-Cigarette Incidents



195 INCIDENTS, 2009–2016

SOURCE: U.S. FIRE ADMINISTRATION

Rewrapped battery brands often advertise inaccurate or ambiguous ratings. For example, we have found rewrapped batteries for e-cigarettes having labels indicating a 30-ampere rating that have actually turned out to be good for only 20 A. In such a case, if the product requires 30 A of current, the battery will be stressed and, possibly, damaged. While not all rewraps have exaggerated ratings or use low-grade batteries, e-cigarette device manufacturers should of course be cautious when purchasing batteries online. And if they do buy rewrapped batteries, it's their responsibility to test them thoroughly in-house to confirm that they're safe and that they live up to their ratings. Manufacturers should also make reliable spare batteries readily available so that if a battery fails, the user will be less likely to buy a new battery from an untrustworthy source.

Some companies are adding so-called authentication stickers to their battery labels, but this anticounterfeiting measure is worthless because it, too, can be counterfeited. Counterfeit Li-ion batteries—which have also been reported in cellphones, laptops, hoverboards, and cameras—can be created by recycling, remarking, tampering, and cloning. A Hong Kong–based investor told the news outlet Quartz that "there are between 50 and 100 e-cigarette manufacturers in China alone who supply 100 to 200 brands globally." How many e-cigarette batteries are counterfeits can't be determined, but my laboratory at the Center for Advanced Life Cycle Engineering at the University of Maryland has found counterfeit parts in all kinds of electronics, including weapons systems procured by branches of the United States military. It would be strange indeed if these parts were *not* used in e-cigarette devices.

Indeed, we know for sure of at least one use of a counterfeit battery. My group was asked to investigate a battery that caught fire in the pants pocket of an e-cigarette user, badly burning his leg. The battery label identified a company named MXJO as the manufacturer and listed a Taiwanese website, www.mxjo.tw, now apparently defunct. That website provided a street address, but I found that no such address existed. Shenzhen MXJO Technology Co. (MXJO) has since told me that it has no manufacturing in Taiwan.

No specific laws govern the safety of e-cigarettes. But some government agencies have at least begun investigating the problems. In the United States, for example, in April 2017, the FDA conducted a two-day public workshop on "Battery Safety Concerns in Electronic Nicotine Delivery Systems (ENDS)" in an attempt to gather information on battery overheating, fire, explosion, and other failures. The conclusion was that the widespread availability of unvetted Li-ion batteries means that e-cigarette manufacturers must shoulder the burden of testing them, designing their systems for worst-case conditions, and making the risks known to the consumer.

In the absence of laws or regulations on e-cigarettes, legal liability may be the best way to apply pressure to makers. Already, courts have made decisions holding companies supplying e-cigarettes accountable for defective batteries. For example, in 2013 Jennifer Ries was charging her e-cigarette using the USB port in her car when the Li-ion battery exploded, giving her second-degree burns. A jury for the State Court of Southern California ruled against the e-cigarette company and awarded Ries \$1.9 million for her injuries.

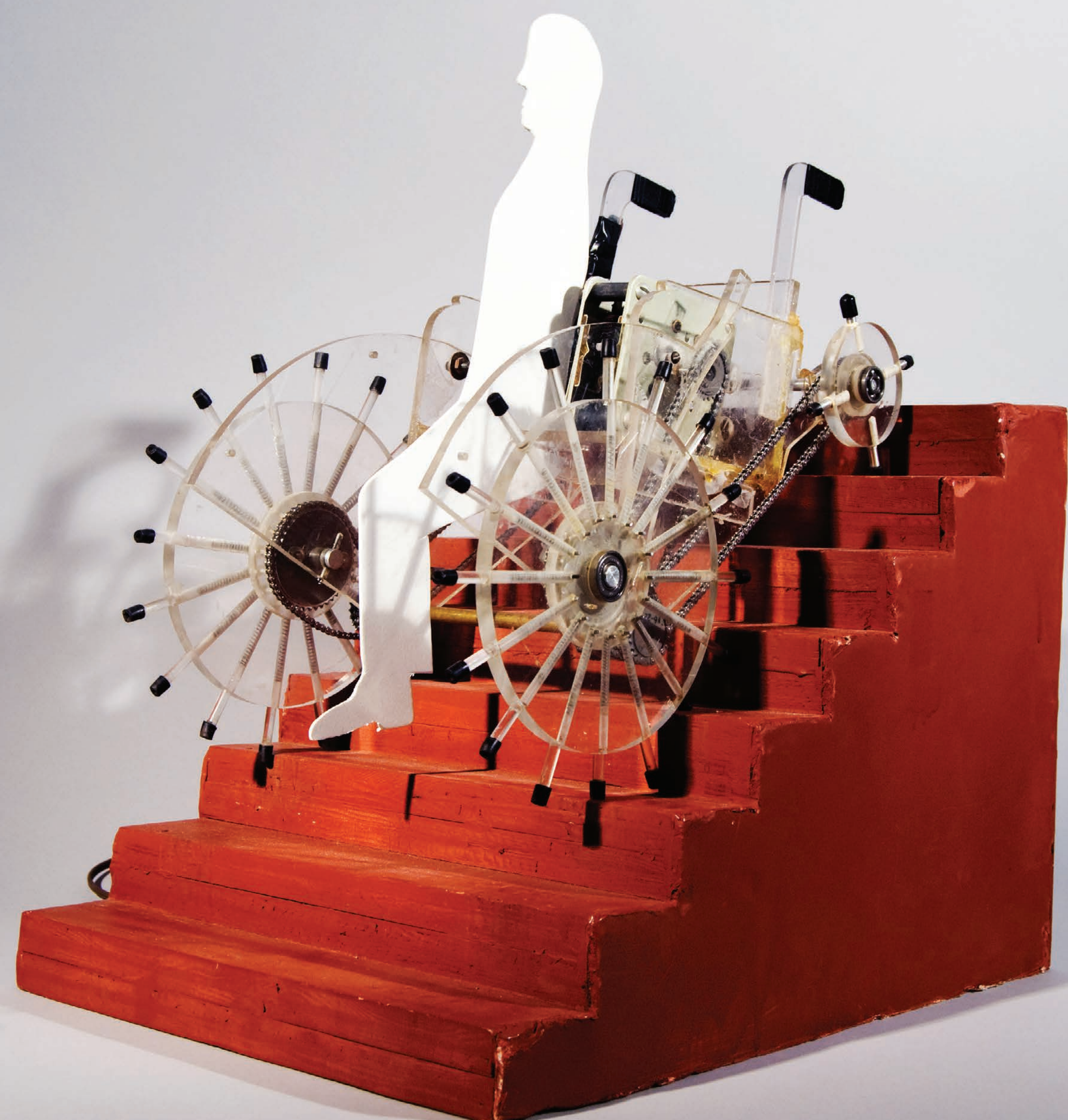
In the meantime, it is best that consumers buy brand-name batteries directly from reliable sources. The entire point of e-cigarettes is the health advantages gained by removing tars and other carcinogens from the smoke. It would be a shame if these advantages were undermined by public fears about devices that blow up or burn people instead. ■

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/explodingecigs0718

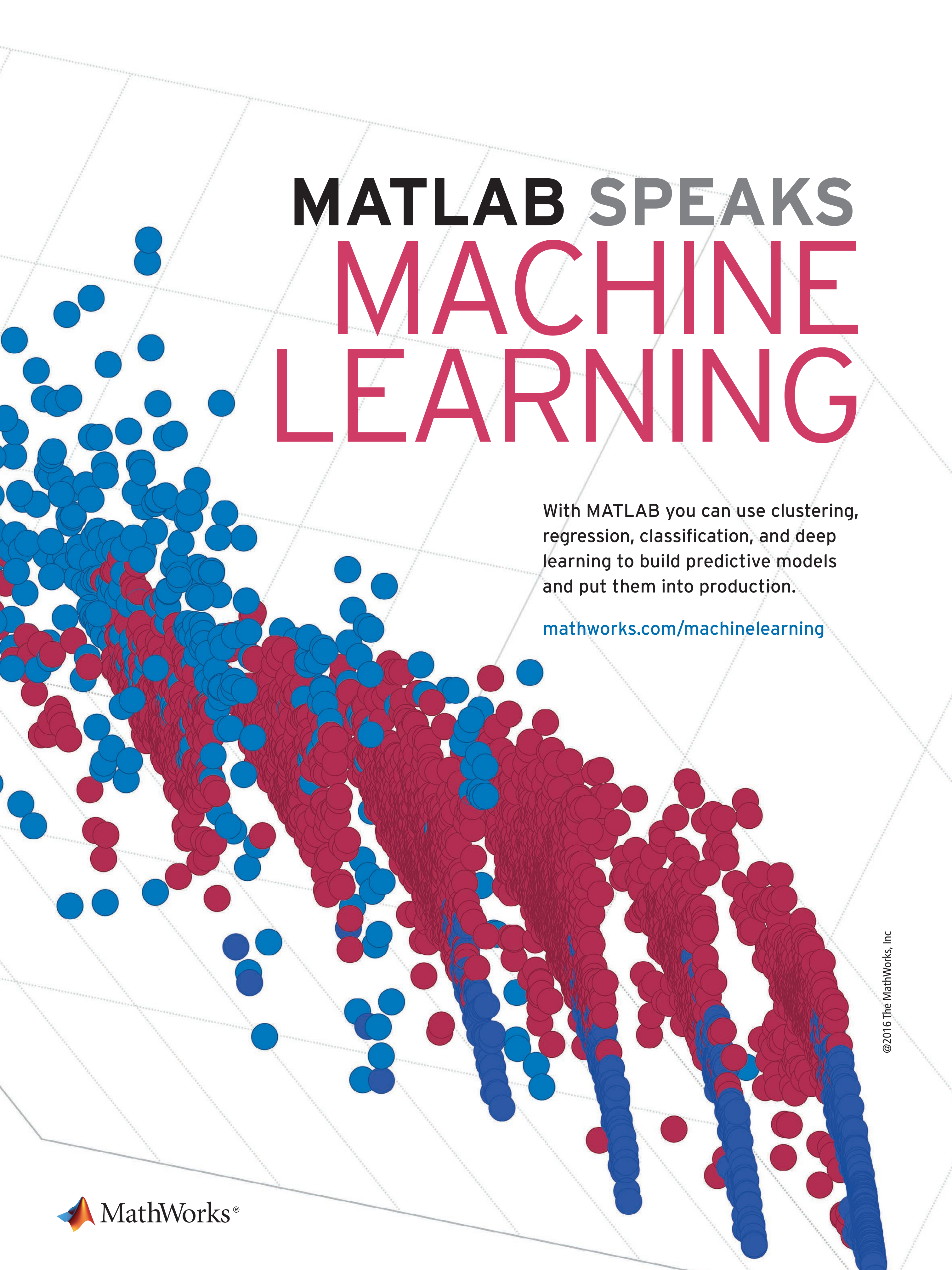
THE WHEELCHAIR THAT MIGHT HAVE BEEN

In 1959, the U.S. National Inventors Council, a clearinghouse for inventions that might have military use, sponsored a design competition for a stair-climbing wheelchair. Ernesto Blanco submitted his idea and created this one-quarter scale model as a proof of concept. He didn't win the US $5,000 prize—in fact, the council never picked a winner. But Blanco went on to invent numerous aids for people with disabilities because he viewed such work as a form of social justice. "Engineering is a service profession," the engineer told an interviewer in 2002. "It is about improving things for mankind." ■

↗ **For more on stair-climbing wheelchairs, go to https://spectrum.ieee.org/pastforward0718**



MIT MUSEUM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