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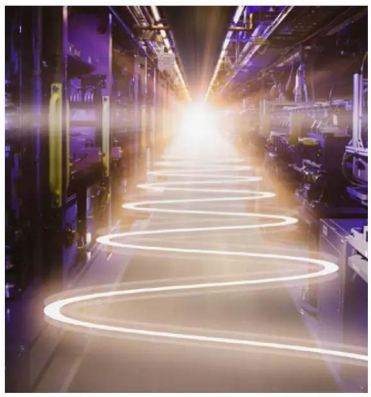

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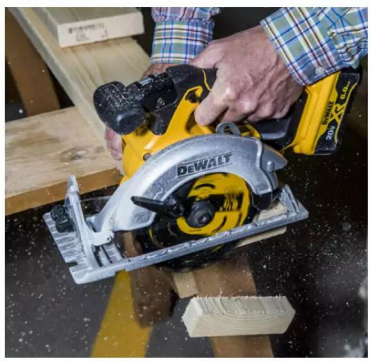
Exciting uses for a powerful, new x-ray laser, the math behind Las Vegas's infamous Sphere, how to correctly use a fire extinguisher, and more. **p.5**



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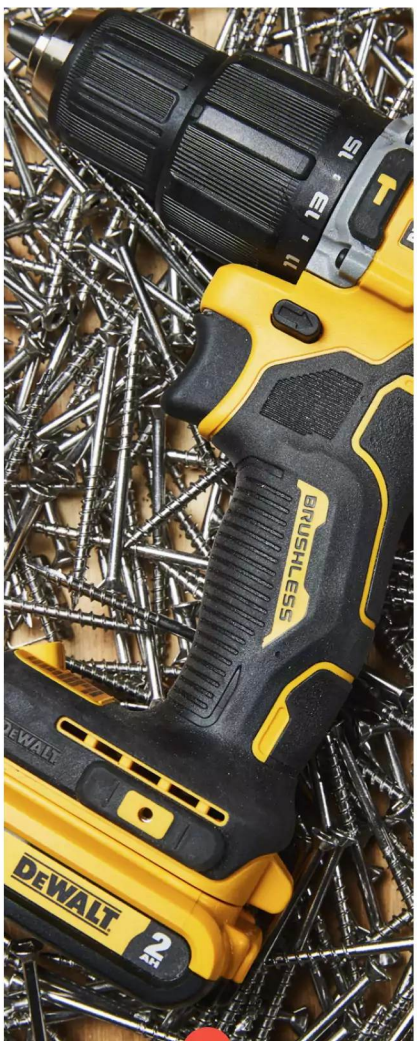

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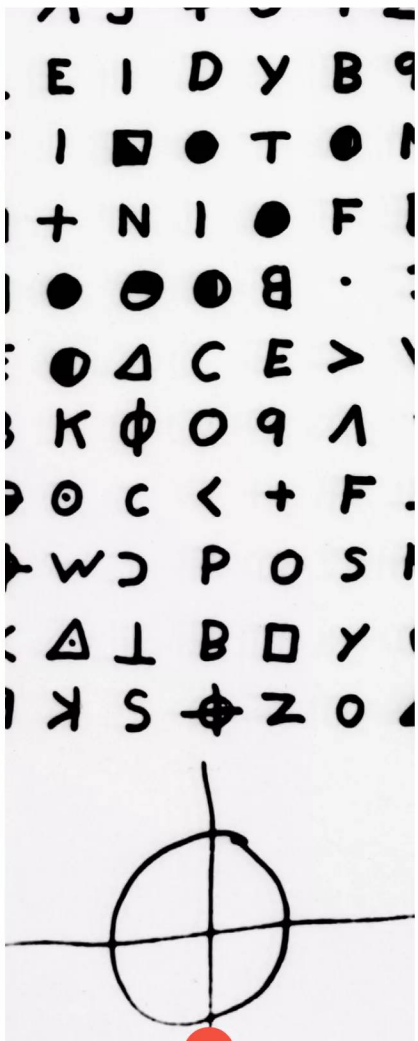
Popular Mechanics Tool Awards 2024

Best-in-class tools and accessories we tested this past year.
By Popular Mechanics *Editors*



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For more than 50 years, the Zodiac Killer's '340' cipher had stumped experts. *By Kathryn Miles*

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By Sophia Chen

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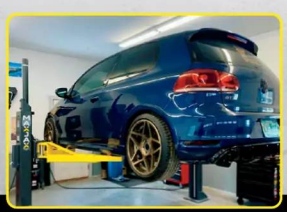

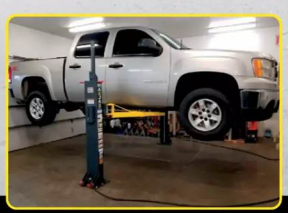

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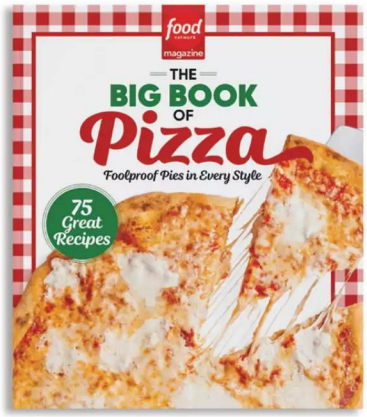

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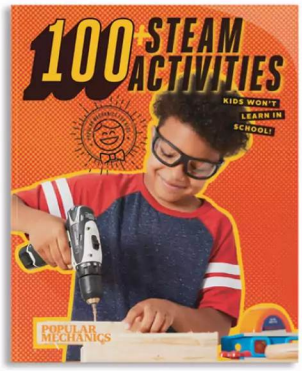

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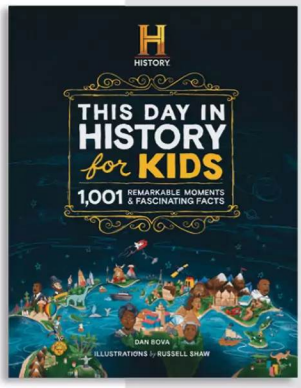

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Can't Stop Thinking About

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WHAT THE WORLD'S MOST POWERFUL X-RAY LASER WILL DO FOR SCIENCE

DEEP UNDER MENLO PARK, California, there is a three-mile-long machine operating in a tunnel that scientists are keeping colder than even some of the deepest reaches of space.

Maintaining this patch at a temperature of –456 degrees Fahrenheit—around 3 degrees higher than absolute zero, the hypothetical temp at which all atomic movement stops—allows scientists at the Department of Energy's SLAC National Accelerator Laboratory to operate the world's most powerful x-ray laser, the Linac Coherent Light Source (LCLS) II.

The LCLS-II laser produced its first high-energy radiation beams

2 Can't Stop Thinking About

on September 12, 2023, ushering in an exciting new era of x-ray-based research.

When at full power, LCLS-II will be able to pump out around a million x-ray pulses per second, about 8,000 times more than its predecessor. This means LCLS-II can create an x-ray beam 10,000 times brighter than the original LCLS, making it the most powerful x-ray laser ever devised.

"LCLS-II represents quite a significant adjustment or paradigm shift for science," says the laser's project director, Greg Hays.

Thousands of researchers are eager to conduct research with the experiment, but what exactly do scientists need such a powerful x-ray laser for?

Shooting molecular movies and advancing quantum physics // The key to the unprecedented utility of LCLS-II is its ability to produce so many high-energy light pulses per second and to focus these on precise areas through x-rays' short wavelengths.

This lets scientists capture snapshots of reactions happening on an atomic level on a scale from one billionth of one millionth of a second (femtoseconds) to one billionth of one billionth of a second (attoseconds).

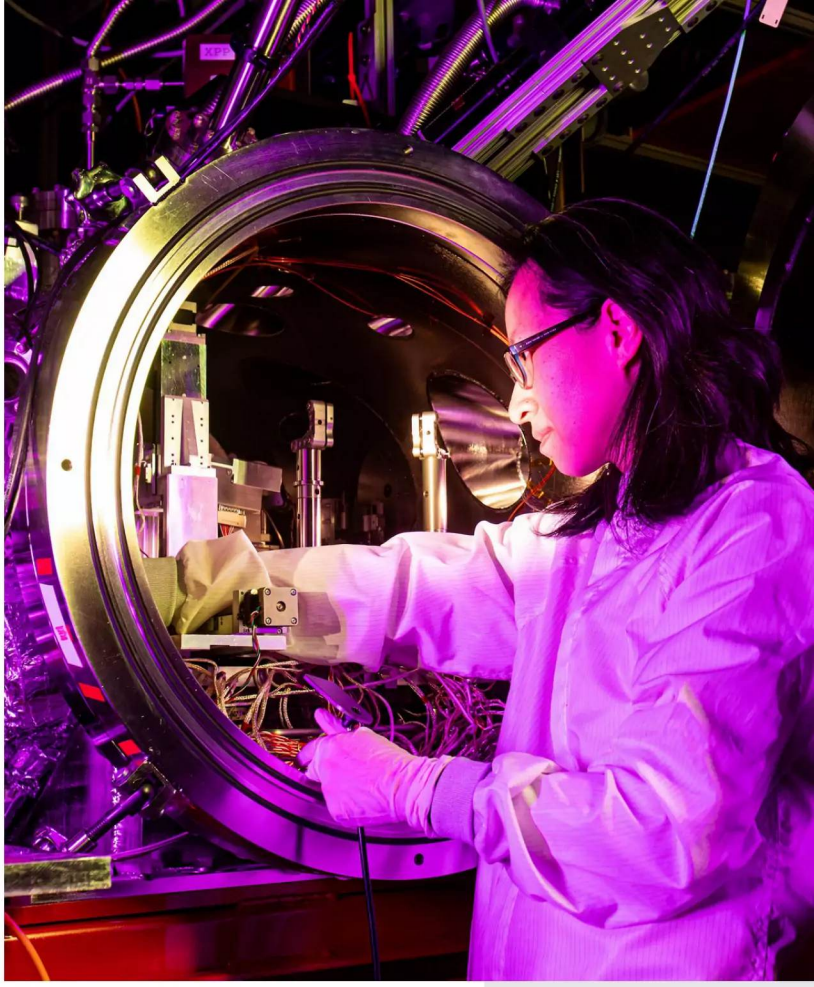
LCLS-II will allow researchers to spot and record chemical events that happen on incredibly short timescales and create detailed "molecular movies." For biology, this means being able to visualize photosynthesis and the action of proteins at speeds and scales never before possible.

Thus, LCLS-II could potentially revolutionize scientists' understanding of the mechanisms that make life possible, which could in turn help pharmaceutical companies develop new drugs.

The timescales at which LCLS-II operate are also on par with those at which electrons move through complex systems carrying energy. This means LCLS-II could assist in getting to the heart of wonder materials like graphene that display incredible and counterintuitive properties derived from quantum physics and, as such, will form the backbone of future ultrafast quantum computers and secure quantum communications.

Additionally, the powerful x-ray laser could provide information that would aid in creating more efficient energy-harvesting solar panels and even the development of more useful (and less harmful) fertilizers.

How does the world's most powerful x-ray laser work? // To generate a million pulses of x-rays per second, LCLS-II accelerates free electrons—as in, "not bound up in an atom"—to near the speed of light around a three-mile-long track using superconductors. When introduced to a magnetic field, these electrons start to oscillate. And when they do this, they emit x-rays—all with the same wavelengths. This makes them ideal for studying subatomic matter.



Staff scientist Meng Liang works on the Coherent X-ray Imaging instrument, located at the LCLS Far Experimental Hall in Menlo Park.

COURTESY SLAC NATIONAL ACCELERATOR LABORATORY

A future upgrade of LCLS-II means it will be able to generate "hard x-rays" of high energy with wavelengths so small, researchers will be able to get down to the bonds between atoms. They'll be able to investigate the orientation of molecules and how this affects chemistry.

Generating a million pulses of x-rays per second produces tons of heat; if the team ran LCLS-II at room temperature, the machine's housing would rapidly melt. So, a liquid helium refrigerator keeps it at temperatures colder than space.

"It consumes about 10 megawatts of power when the machine is fully running flat out. That's just the power needed to keep the machine colder than outer space, about a factor of four or five times more than we use to accelerate the electron beam," Hays said.

In mere dollars and cents, the upgrade to LCLS has cost around $1.1 billion. In terms of time, Hays said planning for LCLS-II has taken around 12 years. But it has all been worth it, with the machine already living up to its potential.—*Robert Lea*

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Why It's So Hard to Mine the World's Largest Lithium Deposit

AN ANCIENT VOLCANO BENEATH NEVADA and Oregon could hold the largest deposit of lithium ever found, scientists revealed last summer in a peer-reviewed paper published in *Science Advances*. This section of land—called Thacker Pass, or *Peehee Mu'huh* to the local Paiute people—has been mined since the 1970s, so the new analysis merely confirms what locals have long known about the area.

Beginning to extract the lithium in earnest would change the landscape for everything from electric-vehicle batteries to lithium-ion smartphone batteries, and could even hasten the switch toward renewable energy plants that rely on grid storage. But setting up a mine to extract the massive deposit of lithium in Thacker Pass is not a simple task: It will require a wholly new process to separate the lithium from its natural clay deposit.

Lithium comes from three sources: the Big Bang, interstellar matter blasted from rays of stars, and nuclear fusion in some stars.

GETTY IMAGES

Volcanic Beginnings // In 1817, Swedish chemist Johan August Arfwedson first discovered lithium in nature as the mineral petalite, in which it is just one of 16 atoms per molecule. Other abundant naturally occurring mineral sources include lepidolite, spodumene, and amblygonite, which range from about 10 percent to 40 percent lithium. Minerals like these are mined, and typically electrified, in order to separate out the commercial form of lithium: lithium carbonate.

But the deposit in Thacker Pass is of a special kind, formed in a volcano millions of years ago. The lithium was part of a volcanic rock, something that can be unusual compared to other sources, because everything is heated to the point of melting, mixed in the caldera of the volcano, and then left there to firm up into something altogether new. The caldera (from the same root as "cauldron") became a lake, whose motions sloughed sediment off the rock and into the lake bottom as clay.

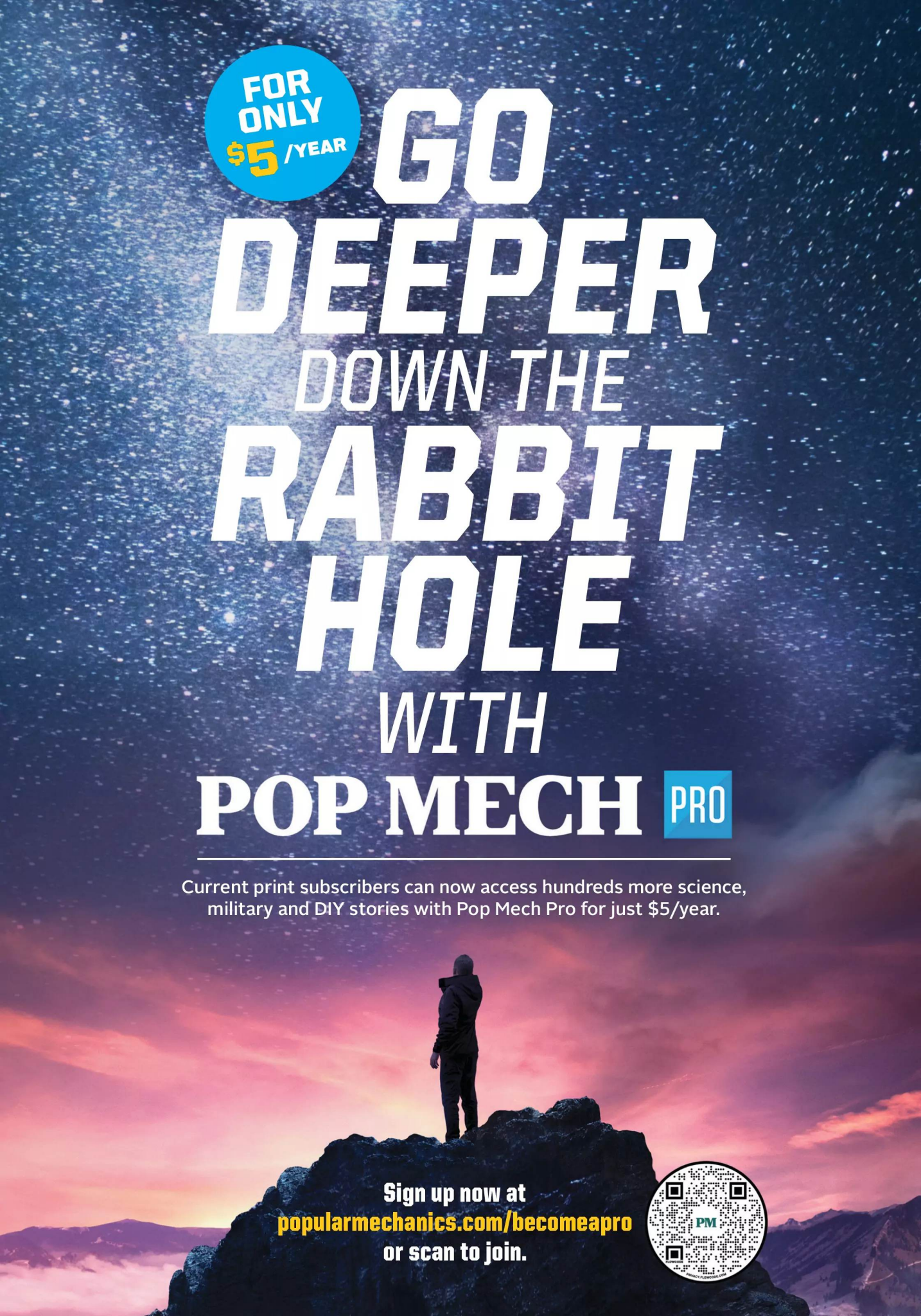
Then, eons later, the volcano became active again. Materials, including lithium, heated, melted, and marinated together. Like the ingredients in a baking recipe, these mixed elements and mineral sediments cooked together into a more uniform area of a mineral called illite, which is essentially clay.

Mining Thacker Pass for Lithium // Today, Thacker Pass is just one portion of the prehistoric caldera's area, but it's the location where the deposit of lithium-containing clay minerals is believed to be richest. And, so far, the special way this deposit was formed, sloughed, and cooked again is like nothing else scientists have seen around the world.

The high concentration of lithium, and in a novel form, is not all that makes Thacker Pass an appealing site for mining, according to the new paper.

Developing a sustainable supply chain for the lithium-ion batteries in electric vehicles and grid storage necessitates the extraction of lithium resources that minimize local environmental impacts. Volcano sedimentary lithium resources have the potential to meet this requirement, as they tend to be shallow, high-tonnage deposits with low waste:ore strip ratios.

In other words, this enormous wealth of lithium is close to Earth's surface, with a lower proportion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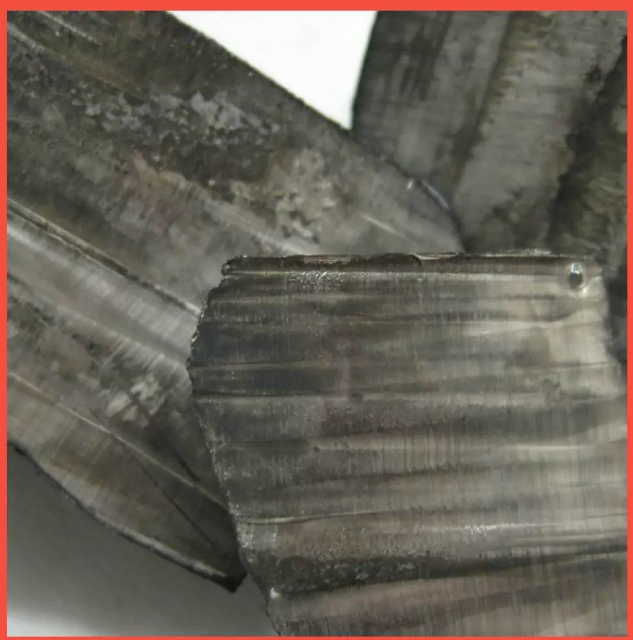
2 Can't Stop Thinking About

of waste than many other mines. That means less energy to dig and extract, as well as less energy to transport and manage the rest of the non-lithium materials found in the mine.

Still, mining the lithium from Thacker Pass will involve a brand-new process. This includes sulfuric acid, a highly corrosive and dangerous substance. At a high level, it will involve the following steps:

- Removing the lithium-containing clay minerals with hydraulic shovels to turn it into a slurry (a mixture of denser solids suspended in liquid—like mixing cornstarch and water together to thicken a soup)
- Separating out sand and rock that does not contain lithium
- Mixing the lithium-clay slurry with sulfuric acid to draw out the metal
- Extracting elemental lithium solution from the slurry, through filters
- Processing the lithium solution into lithium hydroxide for use in batteries.—*Caroline Delbert*



Lithium Is All Around Us // The U.S. Geological Survey estimates there are 100 million metric tons of lithium in deposits on Earth. Experts believe more than half of that lithium can be found in one triangular area of desert in western South America. The aim is to mine 40 million tons in the first year of operation at Thacker Pass. Some sources suggest there is 179 metric tons of lithium there that could be mined.—*C.D.*

WIKIMEDIA COMMONS/DNN87 (LITHIUM); COURTESY US ARMY (TANK)

The Army's Drone-Killing Laser Weapon

THE U.S. ARMY FIELDED ITS FIRST LASER-weapon-equipped unit in October. Based at Fort Sill, Oklahoma, the unit took possession of four laser-equipped Stryker infantry combat vehicles, each mounting a 50-kilowatt-class laser-weapon system. The combination of Stryker and laser can down both artillery, such as mortars and rockets, and drones in-flight.

Sky Sweeper// The four vehicles are known as Directed Energy Maneuver-Short Range Air Defense, or DE M-SHORAD for short. "Directed energy" refers to the laser, "maneuver" refers to the fact that the laser is mounted on a mobile vehicle, and "short range air defense" is the vehicle's officially designated mission.

DE M-SHORAD places a 50-kilowatt-class laser on a double-hull Stryker infantry combat vehicle, the latest version of the Stryker designed to provide

additional protection against improvised explosive devices (IEDs) and ground explosions. An onboard generator provides power to the laser, and the vehicle also sports airborne threat detection, tracking, and targeting equipment.

The result is a self-contained system that doesn't require an entourage of support vehicles and can roll out and provide aerial protection for other maneuver forces like Stryker, tank, and mechanized infantry companies.

The laser on DE M-SHORAD works by focusing an intense beam of laser light on a target. This beam is extremely hot, almost like a thinly focused flamethrower. A laser can burn the wings or rotors off of a flying drone, causing it to suffer structural failure and tumble to the ground. It can also destroy a drone by burning out the onboard circuitry—blinding any cameras that human operators use to steer the drone, or in the case of drones that use fuel-based motors, cause the fuel to ignite, destroying the drone.

Riding Shotgun // DE M-SHORAD is meant to be attached to friendly maneuver forces, such as columns of Abrams tanks, Bradley fighting vehicles, or Stryker infantry combat vehicles, scanning the skies above for enemy drones. If a drone or drone swarm is detected, the system can rapidly shoot them down. The system can also shoot down enemy artillery, and in a May 2022 test, it shot down artillery rockets and mortar rounds.

The ability to shoot down enemy artillery projectiles over a battlefield is a capability no other army has ever fielded before. While technically possible, using expensive guided missiles to shoot down inexpensive unguided artillery rounds made battlefield deployment impractical. Israel's Iron Dome defense system uses $40,000 to $50,000 missiles to shoot down rockets that cost about $300 to $800 each. While this cost ratio is way out of whack, most of the enemy targets it defends are civilian and immobile, and there is no other way to protect them.

The new laser Stryker vehicles promise a more efficient, defender-friendly cost ratio. While the up-front cost of buying DE M-SHORADs is high, the cost per shot amounts to the cost of diesel fuel to generate the necessary electricity to power the weapon.

It also means that, unlike gun- or missile-based systems that rely on individual munitions to make up the ammunition supply, as long as the laser has fuel to power the generator, it can keep shooting. (A laser version of Iron Dome, Iron Beam, is under development and may eventually replace the original Iron Dome.)

The ability to shoot down enemy artillery projectiles over a battlefield is a capability no other army has ever fielded before.

Drones Are Every Tank's Problem // The Army assigned the first four DE M-SHORAD vehicles to Delta Company, 4th Battalion, 60th Field Artillery Regiment, whose regimental motto is: "We rule the heavens." It's unclear how many more of the laser Stryker vehicles will follow, but after drone attacks that destroyed fully modern, main battle tanks in both Ukraine and Israel, drone defense will be a top priority in the armies of NATO and the West. In one example, a $500 drone carrying an $800 PG-7V anti-tank rocket successfully disabled a $4 million Merkava IV tank. It showed that, as much as one might want to chalk up Russian losses to sheer ineptitude, drones can neutralize the tanks of the most advanced, professional armies.

The rise of battlefield drones has been nothing short of astonishing. Battlefield drones are also following an unusual pattern: As they become more sophisticated and dangerous, they're also growing cheaper and easier to field in larger numbers. Countering them requires a weapon that can shoot them down both quickly and cheaply. DE M-SHORAD just might be that weapon.—*Kyle Mizokami*

COURTESY US ARMY

The Sphere has seven concourse levels and an 80-foot atrium with columns twice the height of those at the Pantheon in Rome.

How the World's Largest Spherical Structure Was Built

THE SHINY, NEW LAS VEGAS SPHERE IS more than just a 17,600-seat amphitheater-style venue hosting a U2 residency. Since its opening in September 2023, it's become the world's largest spherical structure, at 516 feet wide and 366 feet tall. Meanwhile, the seating bowl's 160,000-square-foot spherical LED "immersive surface" lights up at full 16K resolution, making it the highest-resolution LED screen on Earth. To add another wrinkle, the world's largest beam-forming audio system—think headphone-style sound without the headphones—tucks behind the immersive surface for a one-of-a-kind experience.

These three world firsts for shape, sight, and sound took *at least* 60 patents to produce, securing the Sphere's spot as a modern engineering marvel.

■ **A Sphere Within a Sphere //** First things first: Why a sphere? "The Earth is round, so for us to have an immersive, transportive experience for our audiences, you need to mimic the environment that people live in," says David Dibble, CEO of MSG Ventures, which is responsible for the building's technology.

The construction was a lesson in tight tolerances. The steel sphere exterior required one of the world's largest cranes—pushed to 90 percent of its capacity—to lift the final 120-ton crown over 500 feet. This created a double sphere that is an exterior freestanding structure independent of the inner sphere, blacked out and wrapped by the external display cage. "We've got a building inside a

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FEELING REJUVENATED

Everyone has aging pains, but CBD can help

By: Beth Giles

Life really does fly by. Before I knew it, my 50s had arrived, and with them came some new gifts from dear ol' Mother Nature—frequent knee pain, stress, low energy and sleeplessness. Now, I'm a realist about these things, I knew I wasn't going to be young and springy forever. But still, with "golden years" nearly on my doorstep, I couldn't help but feel a little cheated. That is until I found my own secret weapon. Another gift from Mother Nature.

It began a few months back when I was complaining about my aches and pains to my marathon-running granddaughter, Jen. She casually mentioned how she uses CBD rub to help with her joint pain. She said that CBD gave her more focus and clarity throughout the day and that her lingering muscle and joint discomfort no longer bothered her. She even felt comfortable signing up for back-to-back marathons two weekends in a row this year. That made even this self-proclaimed skeptic take notice.

But I still had some concerns. According to one study in the Journal of the American Medical Association, 70% of CBD products didn't contain the amount of CBD stated on their labels. And, as a consumer, that's terrifying!

If I was going to try CBD, I needed to trust the source through and through. My two-fold research process naturally led me to Zebra CBD.

First, I started calling my family and friends. Call me old fashioned but I wanted to know if there were people whom I trusted (more than anonymous testimonials) who've had success using CBD besides my granddaughter.

Secondly, I wanted cold hard facts. Diving deep into the world of CBD research and clinical studies, I came across Emily Gray M.D., a physician at the University of California at San Diego (UCSD) Medical School and medical advisor to Zebra CBD who is researching the effects of CBD. Dr. Gray wrote "early results with CBD have been promising and we have a lot of research underway now. I've had several patients using CBD with good success. It's important that you know your source of CBD and how to use it properly."

After hearing it from the doctor's mouth, I returned to my research, asking more people and was amazed by the number of close friends and family who were already on the CBD train. Apparently, I was the only one without a clue! And funny enough, a couple of friends who commented were using the same brand as my granddaughter—Zebra CBD. There was no consensus as to why they were using CBD, but the top reasons given were for muscle & joint discomfort, mood support, sleep support, stress and headaches, as well as supporting overall health & wellness.

Eventually, even the most skeptical of the bunch can be won over. With a trusted CBD source in mind, I decided to give it a go.

When I viewed Zebra CBD's selection online, I was impressed by its array of products, including CBD oils called tinctures, topicals, chewable tablets, mints and gummies. After reading on their website that all their products are made with organically-grown hemp, I ordered... and it arrived within 2 days!

The first product I tried was the Rub. Now this stuff was strong. Immediately after rubbing it on my knee, the soothing effects kicked in. It had that familiar menthol cooling effect, which I personally find very relieving. And the best part is, after two weeks of using it, my knee pain no longer affected my daily mobility.

The Zebra Sleep Gummies, on the other hand, had a different but equally positive effect on my body. To take it, the instructions suggest chewing thoroughly. This was simple enough, and the taste was, well, lemony. After about 15 minutes, a sense of calm came over my body. It's hard to describe exactly; it's definitely not a "high" feeling. It's more like an overall sense of relaxation—and then I fast asleep. Needless to say, I slept great and woke up refreshed. I haven't slept like that in a long time.

While it hasn't been a catch-all fix to every one of my health issues, it has eased the level and frequency of my aches. And it sure doesn't seem like a coincidence how rejuvenated I feel.

All-in-all, CBD is one of those things that you have to try for yourself. Although I was skeptical at first, I can safely say that I'm now a Zebra CBD fan and that I highly recommend their products.

Also, I managed to speak with a Zebra CBD spokesperson willing to provide an exclusive. If you order this month, you'll receive $10 off your first order by using promo code "**PM10**" at checkout. Plus, the company offers a 100% No-Hassle, Money-Back Guarantee. You can try it yourself and order Zebra CBD at ZebraCBD.com/PM or at 1-888-762-2699.

2 Can't Stop Thinking About

building," says Paul Westbury, executive vice president of development and construction at Sphere Entertainment.

Both required intricate planning to construct with supports during sequencing. "Getting the pieces to fit is not as easy as it seems," Westbury says. The team had to plan installation based on how hot the sun was (heat makes the steel expand), while dealing with building something akin to an igloo. "You build it up layer by layer until you put the cap piece in," he says. "It is a little bit wobbly as you go up."

■ **Seen From Space //** The 580,000-square-foot, fully programmable LED exterior creates a vivid canvas of 256 million colors, bright enough to be seen from space.

Light-emitting diodes certainly existed prior to this project, but the ability to light up the entire building—it's appeared in Las Vegas cityscape photos as everything from an eyeball to a basketball—required a new approach to handle the curvature and geometry. "LED sticks just aren't going to work," Dibble says.

The solution: LED "pucks"—so named because they are roughly the same size as a hockey puck—each made up of 48 diodes. All 1.2 million pucks are backfilled in black silicone for weather sealing and to remain nonreflective. The pucks, assembled amid 400 LED mega panels attached to a steel diagrid, are spaced 9 inches apart for a high-resolution outdoor screen calculated for ideal resolution at 978 feet.

■ **Wrapped in Experience //** Inside the Sphere, the immersive 160,000-square-foot surface wraps up, over, and around the audience with full 16K by 16K resolution.

With a display about the size of two full soccer fields, the 189 million diodes needed to center every 9 millimeters. "That is pretty tough," Westbury says. "Then it gets tougher. The human eye is incredible and picks out any little variance in geometric position." To trick the human eye into this fully immersive experience, the tolerances on the diode placements are wildly tight, just the thickness of a blade of grass.

"If you look at it, it's photo-real," U2's Bono told Apple Music. "It's at a level of resolution that you will not even detect the shape of the Sphere."

■ **The Sound of Sensation //** The Sphere has 164,000 speakers. They're all tucked behind the immersive surface, so visitors don't see even one.

The immersive sound uses 3D audio beamforming technology and wave-field synthesis to target audio to the seating bowl, sending unique audio content—whether different languages, different instruments, or unique sound effects—to varying locations within the venue. Dibble says the magic in the audio system is the digital processing that happens in real time behind the scenes. The speakers act like a flashlight beam that can pinpoint light or spread it out.—*Tim Newcomb*

The Math Behind the Sphere // Engineers embraced centuries-old mathematical formulas and laws as well as some incredibly contemporary interpretations to build the Sphere, ultimately creating an entire exhibit in the building's Atrium to pay homage to it. Here are just a few examples we love: **1 → Law of Sines:** This law helped in calculating architectural angles across the building, from the pitch of the Atrium escalators to the curve of the archways. **2 → Navier-Stokes equations:** This set of formulas replicates the paths of nature to help calculate the flow and thrust of the Sphere's 4D effects, like wind. **3 → Kirchhoff- Helmholtz Integral:** This equation keeps sound from scattering. With the world's largest beam-forming audio system, the Sphere can provide optimal audio for every seat in the venue. **4 → Geodesic math:** A sphere is truly a love affair with triangles. The laws of geodesic math are action-packed at the Sphere, where hundreds of interlocking triangles create the shape and structure.—*T.N.*

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750	+150	6	$ 72.50	$32.50	29%
1100	+400	10	$110.00	$47.50	36%
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Super Plugs Precut plugs 3 inches by 3 inches READY TO PLANT Packed in trays of 15 Super Plugs. Plant minimum 1 plug per 4 sq. ft.

Super Plugs	Free Plugs	Tray	Your PRICE	+Shipping	SAVINGS
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The Right Way to Use a Fire Extinguisher

A FIRE EXTINGUISHER IS MORE THAN A tool that puts out a fire. It can be the arbiter between life and death. Consider this: Fire with access to air and fuel will double in size every 30 seconds. In three minutes, a fire that starts out the size of one 5-gallon bucket becomes the size of 64 burning buckets. Just 180 seconds after it begins, a fire can be transformed from a nuisance to a room-size, life-threatening inferno.

What we state above is a pillar of firefighting science, and we came across it in taking a class on using a fire extinguisher at the newly opened Allentown Fire Training Academy in Pennsylvania. Our instructor was John Christopher, the fire department's captain of public affairs. Every week, he teaches a wide cross-section of the community the intricacies of using a fire extinguisher. Construction company employees, truck drivers, nursing home employees have all taken his brief class.

Like learning CPR or first aid, training yourself to use a fire extinguisher can save your own life and property, or that of someone else.

The most common fire extinguishers in residential and commercial environments are ABC type, meant for wood and paper, combustible liquids, and electrical fires.

■ **Call 911 then PASS //** Given the rapidity with which fire spreads, taking time to first call 911 seems counterintuitive. "The first step is to call 911," Christopher says. "Always." If more than one person is available to fight the fire, have one person call while another battles the blaze. "The biggest fires that we've had to fight," he says, "resulted from a delay in someone calling the fire department."

To use the fire extinguisher, slide or lift the fire extinguisher off its bracket, then use the PASS method to extinguish the blaze.

→ **PULL** the locking ring from the extinguisher's handle.

→ **AIM** the fire extinguisher's nozzle at the base of the fire. You should be standing far enough from the fire to not be in immediate danger from it, but not so far that the extinguisher will be ineffective. In most cases, that means standing 8 to 10 feet from the fire.

THOMAS HENGGE

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→ **SQUEEZE** the fire extinguisher's handle to begin the flow of firefighting agent.
→ **SWEEP** the extinguisher's nozzle over the base of the blaze.

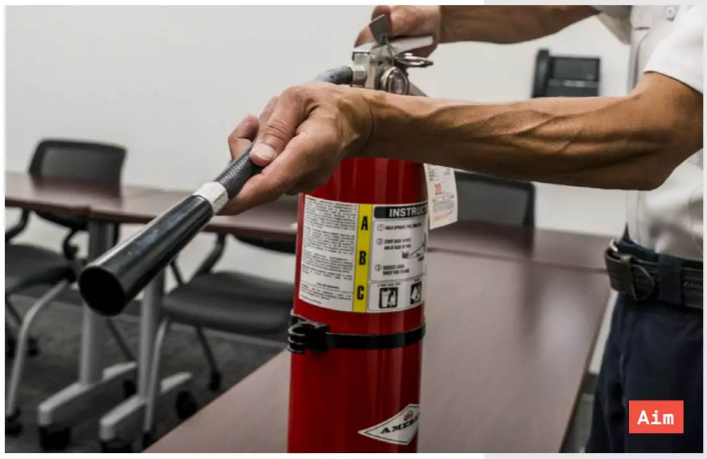
■ **The Fine Points //** If calling 911 is your first step, then an equally important goal is to get people out of the building, out of the vehicle, or out of harm's way. "Always protect yourself and others first," Christopher says. Even if the blaze is immediately extinguished, no harm is done by evacuation. And this is even more important if there are children, elderly, or disabled people present.

"Never let the fire get between you and your exit," Christopher says. One minute it might seem that you've got the upper hand, but the next thing you know, the fire has grown and it has blocked your exit. It's critical that you remain vigilant. Keep your exit at your back as you battle the fire.

"When in doubt, get out," he adds for emphasis.

If the fire hasn't gone out, but the extinguisher has, then you've done everything you can. A closed door (assuming there is one) is one of the surest ways to starve a fire of the air it needs to spread.

There are two other firefighting pillars worth remembering, Christopher says: First, never turn your back on a fire. Even after you think you have it out, keep your eye on it until the fire department has arrived. Second, empty the fire extinguisher. You can't extinguish a blaze and then put the partially discharged extinguisher back on the mounting bracket. It will need to be serviced or, in the case of inexpensive homeowner-grade extinguishers, disposed of.—*Roy Berendsohn*

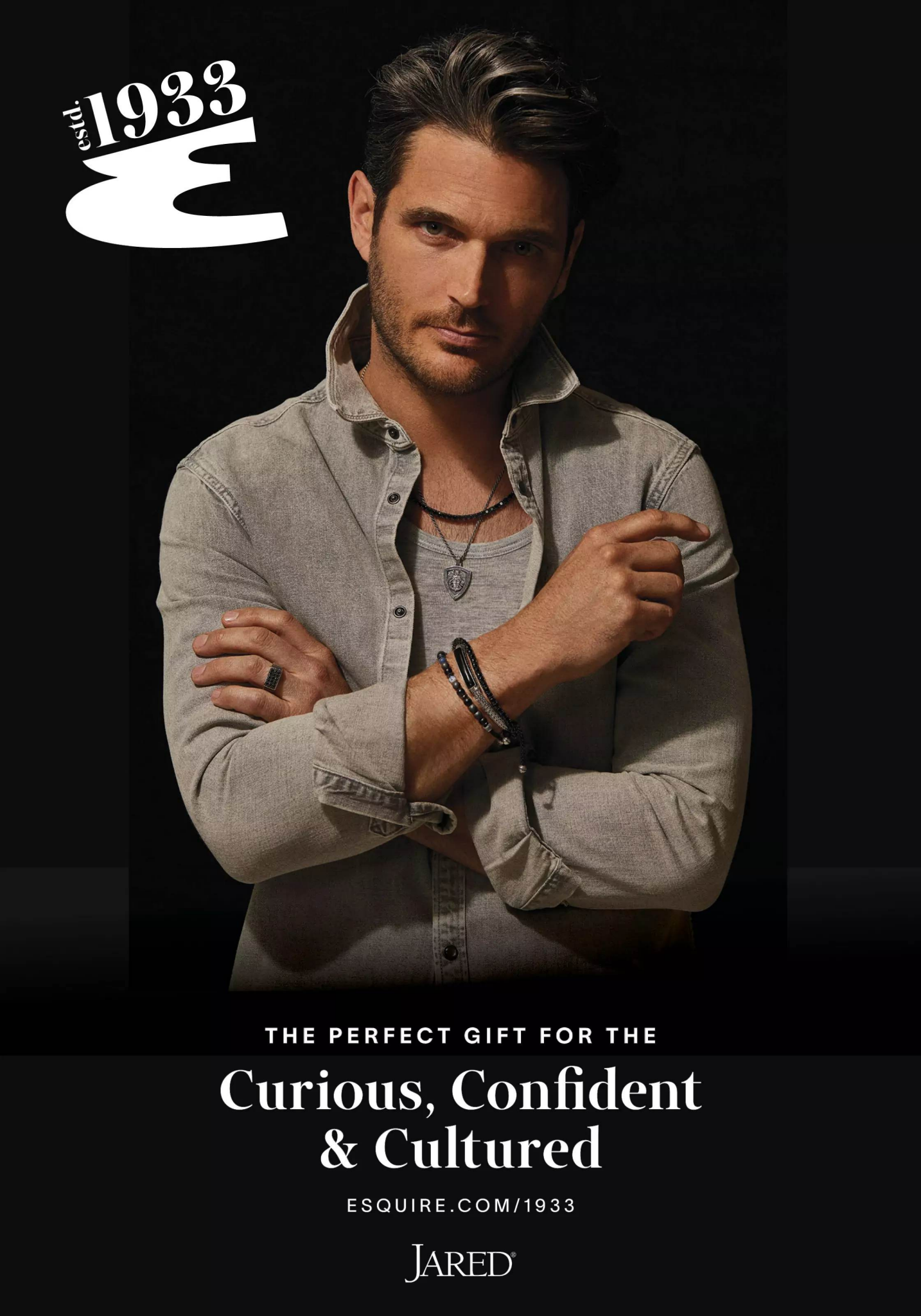


WHAT DA VINCI USED TO PAINT THE MONA LISA

New research on the *Mona Lisa* suggests Leonardo da Vinci may have crafted a new type of paint mixture for his early 16th-century masterpiece—and that the recipe may have endured for hundreds of years. By analyzing a minuscule spec of paint culled from a spot the diameter of a human hair in the work's base layer, a team of researchers revealed the chemical makeup of the substance. In the resulting paper, published last fall in the *Journal of the American Chemical Society*, the team described a "singular mixture of strongly saponified oil with high lead content and a cerussite-depleted lead white pigment."

The real eye-catcher, though, was the presence of plumbonacrite—a rare compound found stable only in an alkaline environment. "Leonardo probably endeavored to prepare a thick paint suitable for covering the wooden panel of the *Mona Lisa* by treating the oil with a high load of lead II oxide, PbO," the authors wrote.—*T.N.*

THOMAS HENGGE (FIRE EXTINGUISHER); GETTY IMAGES (MONA LISA)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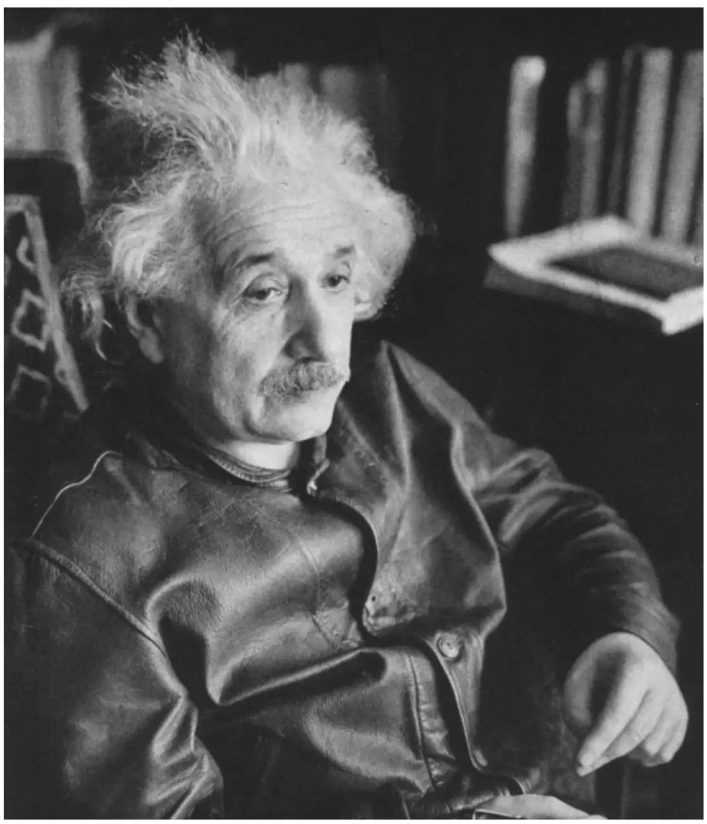
How This Particle Could Break Our Understanding of Reality

EINSTEIN'S SPECIAL THEORY OF relativity teaches us that nothing can accelerate past the speed of light. But what if, when you were born, you were already moving faster than light? What would that look like?

Turns out, the type of particle that could enable such a strange circumstance already has a name—the tachyon—and its existence wouldn't just break our understanding of physics, but our grip on reality as we know it.



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The Rules for Traveling Faster Than Light // As objects move faster, they gain more energy. But relativity tells us that mass and energy are the same thing (as in $E=mc^2$). An object approaching the speed of light picks up an infinite amount of mass, which would require an infinite amount of energy to push—therefore, all massive objects are forever restricted to speeds below that of light.

Yet relativity tells us that if a special particle were to appear on the scene, already traveling faster than light, then it would be forced to move at light speed forever.

The hypothetical tachyon particle could beat light speed. The problem: Its existence would rewrite a fundamental aspect of our physical universe.

Tachyons Don't Follow Cause-and-Effect Logic // The issue here is causality—the principle that everything has a cause, that every cause leads to an effect, and that every effect comes from a cause. For example, if I want to put coffee in my mug (an effect), I have to pour the coffee from the pot into the mug (a cause).

Causality is how we make sense of the flow of time. This unbroken chain of causes and effects forms the basic structure of experience. Tachyons break that chain.

Or the Speed of Light // Special relativity also tells us that the speed of light, the ultimate cosmic speed limit, is also the fastest possible way for one cause to lead to an effect. If I want to tap your shoulder and you're far away, I have to travel to you first.

The limit on the speed of moving objects also imposes a limit on the speed of causality. For instance, if you were to move to the Andromeda Galaxy, 2.5 million light years away, but I had only an hour and a half to get there and tap your shoulder, I'd be out of luck.

With tachyons, however, it's possible to violate those rules, because tachyons travel faster than light.

The Time-Traveling Particle // For example, let's say I'm sitting on Earth and you're in a spaceship, far away. We each have a special transmitter that can send and receive tachyons.

I send you a message, and it reaches you faster than light. That means that if you have a telescope pointed back at me, you'll receive the message before you see me sending it, since the light from me reaching your telescope is limited to the speed of light! Then, you can compose a return message

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and send it back to me; again, I would receive the message before you ever saw me send the original message—meaning you're effectively sending your reply back in time, a special trick available only through faster-than-light tachyon particles.

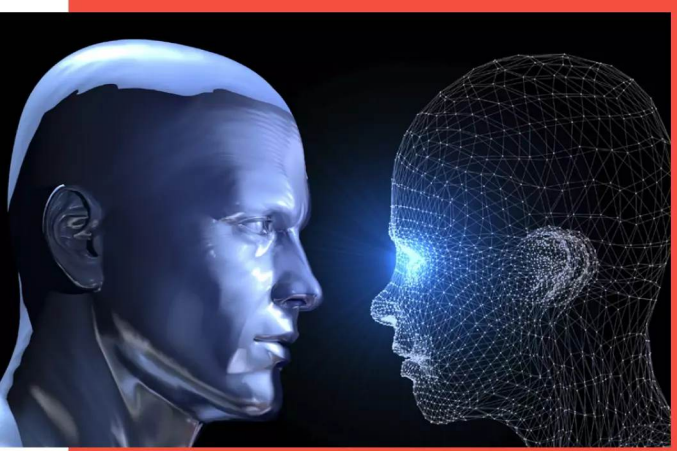
This is bizarre, but it's not causality-breaking—yet. So, let's start messing with reality. Within this imaginary setup, let's pretend that my tachyon transmitter has a self-destruct mechanism, but only if it receives a secret coded message that you know. When you reply to my transmission, you send the self-destruct signal to my transmitter.

Because tachyons can travel faster than light, your response to my initial message actually arrives before I sent anything.

But your response instructed my transmitter to self-destruct, making it impossible for me to send my message in the first place. Yet, the only way to get the self-destruct signal was for me to send my message...and for you to respond.

Which is it? Did I send my message, or did my transmitter self-destruct? It's a paradox caused by the presence of those faster-than-light tachyons, breaking the normal order of cause and effect. Because tachyons can travel into the past, they can trigger effects to occur before their causes, which leads to all sorts of ridiculous paradoxical scenarios.

Can Tachyons Exist? // We have no proof that tachyons don't exist. There is nothing in the theory of relativity itself that rules out their possibility. But if they did, they would completely shatter our understanding of reality. Physics would break down, since physics is the story of cause and effect at a fundamental level, and the logical flow of time would become a tangled, nonsensical mess.—*Paul M. Sutter*



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IF EMBODYING SOMEONE ELSE IN VR CAN CHANGE YOUR BEHAVIOR

What if you could take on the intelligence, charm, or confidence of another person just by pretending to be them? Researchers are exploring a type of embodiment in the virtual reality (VR) space called the "proteus effect" to see if it's possible. Scientists at Stanford coined the term in 2007, and it describes short-term behavioral changes gained through embodying a virtual avatar.

At its core, embodiment in VR is a way our minds make meaning out of multiple streams of information, says Daniel Harvie, PhD, a program director of the University of South Australia's Masters of Advanced Clinical Physiotherapy program. He published a paper in 2022 that explores whether VR embodiment of superheroes can help treat chronic back pain.

"We don't perceive our body directly; instead we perceive a version of our body that is filtered through our nervous systems and influenced by past experiences, beliefs, things people tell us, hormones, mood, and more," Harvie explains. "[With embodiment], there is a voluntary suspension of belief, because on some level, the digital body actually feels like you, while on another level, you know it's not." In other words, your body is receiving mixed signals about what is you and what isn't you.

Part of what makes VR a powerful platform for embodiment is that it is both wholly immersive and synchronous to a user's real-life actions. However, any changes felt through the embodiment are still based on the user's filtered perception of the experience and not necessarily on immutable truth. Still, one of the most promising parts of VR embodiment is that behavioral changes can be felt even after the headset has been removed, Harvie says.

"Once you leave VR, you disembody the avatar. But you might be left with feelings that are still consistent with the avatar," he says. "For example, our participants have embodied characters like the Incredible Hulk, and for at least a short period after, they felt stronger and more agile."—*Sarah Wells*

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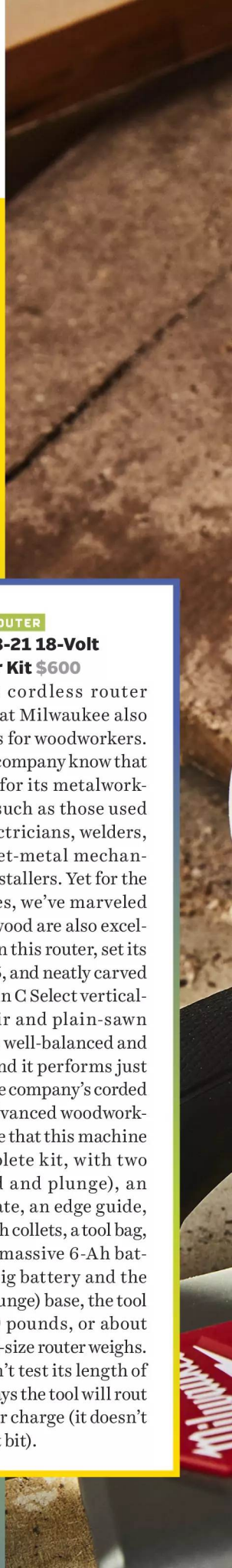
For more than 120 years, *Popular Mechanics* has been a heavy-duty brand. We see no reason to change that now. That's why producing our annual Tool Awards package involves countless hours researching, testing, and writing. It's worth it, because tools are important to us. And we know that tools are important to you, too—and that they help you perform well. You have skin in the game. You own things and you work on them, whether it's your house, car, gadgets, or furnishings. And having spent more than 120 years representing the interests of the owner-builder and the owner-repair person, we take the obligation seriously. This year's awards will help you profit from our work.



BEST FULL-SIZE ROUTER

Milwaukee 2838-21 18-Volt Cordless Router Kit $600

This top-notch cordless router demonstrates that Milwaukee also builds great tools for woodworkers. Observers of the company know that it is well-known for its metalworking equipment, such as those used by plumbers, electricians, welders, fabricators, sheet-metal mechanics, and HVAC installers. Yet for the last three decades, we've marveled that its tools for wood are also excellent. We turned on this router, set its six-speed dial to 5, and neatly carved out deep rabbets in C Select vertical-grain Douglas fir and plain-sawn maple. The tool is well-balanced and easy to handle, and it performs just as flawlessly as the company's corded counterparts. Advanced woodworkers will appreciate that this machine comes as a complete kit, with two bases (standard and plunge), an auxiliary faceplate, an edge guide, ¼-inch and ½-inch collets, a tool bag, a charger, and a massive 6-Ah battery. With that big battery and the standard (non-plunge) base, the tool weighs exactly 9 pounds, or about what a corded full-size router weighs. Although we didn't test its length of cut, Milwaukee says the tool will rout 225 linear feet per charge (it doesn't specify with what bit).

PHOTOGRAPHY BY TREVOR RAAB

POPULAR MECHANICS TOOL AWARDS 2024

BEST COMMERCIAL-DUTY CONSTRUCTION TOOL

Bosch GNB18V-12N 18-Volt Concrete Nailer $504

We looked askance at this tool when we heard about it. A cordless nailer for concrete—really? Then we test-fired it and were pleased with what we found. It's a reliable shooter. We drove ¾-inch nails into concrete without trouble. They come in collated strips, and you drop them into the nailer's 22-shot magazine like you would a finish nailer. Slide the magazine lock behind the fasteners, click in a battery, and pull the trigger. Suppose you want to fire individual non-collated masonry nails, even non-Bosch nails. No problem, the Bosch will do that. Longer nails? Yep. The tool is rated to fire nails up to 1½ inches in length.

BEST COMPACT HAMMER DRILL

Ingersoll Rand Model D5421 20-Volt Hammer Drill Driver $264

Ingersoll Rand is well-known for industrial-duty pneumatic tools, so it comes as no surprise that its line of compact 20-volt cordless power tools exhibits gutsy performance. We took this compact hammer drill and chucked in bits for drilling masonry, a ¾-inch spade bit for pressure-treated lumber, and a ⅜-inch drill for 1/16-inch steel. Then we drove 3-inch lag screws into a pressure-treated 4x4. The gray drill handled each without complaint. The tool is rated for 1,100 inch-pounds of torque and is equipped with the same type of 24-position clutch ring that you find on drills twice its size. By itself, the drill weighs 3.4 pounds. Depending on which battery you attach, it weighs 4.2 pounds to 5 pounds. In other words, it's solid.

MOST VERSATILE PLIERS

Klein Tools Plier Wrench D53010 $50

Leave it to Klein Tools to come up with this thing: a plier wrench. With the jaw in one position, you have basic sliding jaw pliers. Press the detent bar on the handle and move the jaws up and down, from ¼ inch to 2 inches. However, at the bottom of the lower jaw's travel, you can detach the jaw. Then, turn it around so that its toothed end is facing up. Now the tool functions more like a pipe wrench. You might think that the idea of a removable jaw with two positions will be fussy to put on and take off, or won't grab securely. Think again. The tool works well on pipe and fittings with the jaw in either position. It's remarkably versatile and well-designed.

BEST HOLE SAW KIT

Disston Blu-Mol Xtreme QuickCore Hole Saw Kit E0100198 $201

Suddenly, it's no big deal to make a hole in concrete block. No, really—we're not pulling your leg. Attach one of these carbide-tooth hole saws into a drill with sufficient power and a ½-inch chuck, and you've got yourself a tool that can make a hole with minimum dust, noise, and fuss. The good news gets even better: The saw's mandrel has a spring-loaded mounting knob that allows you to quickly detach the saw from the mandrel. The concrete plug that you produced in the process of drilling that hole pops right out of the saw. I don't know if I'd say this is fun work, exactly, but it comes pretty close. Ten hole saws, one mandrel, and a spare pilot bit are all included in the blow-molded case that secures with two clasps.

BEST TRIM ROUTER

Flex FX 4221 24-Volt Fixed-Base Trim Router $199

If you miniaturized a full-size router and turned it into a cordless power tool, that's what you've got with the Flex, the most recent example of the company's power tools to impress us. Like a full-size router, its cut depth is adjustable one of two ways: Undo the latch on its base, press in on the tabs on its depth-adjustment ring, and slide the base up and down. To fine-tune that depth, rotate the ring and read out the amount of adjustment on the ring's 1/64-inch graduations. The tool may be small, but it's stout. Its dial-adjusted speed control (through six settings) ranges from 16,000 to 31,000 rpm—more than enough speed control for small-diameter router bits used in shaping and trimming thin material. For precision routing, you can use the tool with its detachable fence or slide it along a straight edge, since one edge of the router's base is flat.

POPULAR MECHANICS TOOL AWARDS 2024

LOWEST PRICED HAMMER DRILL

Harbor Freight Hercules HCB92B 20-Volt Hammer Drill $79

Harbor Freight, which owns the Hercules brand of contractor-grade power tools, classifies this drill as compact, meaning that it's smaller and lighter than typical. For this class of power tool, however, it is actually a bit larger than the tools offered by other manufacturers. Without a battery, the hammer drill weighs 3.4 pounds. That's about 0.75 pound heavier than other tools in this class. We don't find it objectionable; we think it points to robustness. The more important point, however, is that there's nothing compact about this drill's performance. The tool reliably spun a 1½-inch spade bit and drove big lag screws. It will make a hole in concrete or mortar without complaint. And the price-to-performance ratio is very good. By the way, that price includes a side handle, a welcome accessory, particularly with torque-rich tools like these.

MOST PORTABLE WELDER

ESAB Renegade Volt ES 200i Welder $3,600

Welding doesn't get more compact or portable than this cordless welder powered by DeWalt batteries. ESAB's welder is a breakthrough in that respect. You don't need a truck; you could put this thing in the trunk or the back seat of any car. Setup takes minutes: Just slide in the four DeWalt Flexvolt batteries, adjust the welding parameters on the digital readout screen, attach your work lead, and weld as you would normally. We ran 3/32-inch 6010 and 1/8-inch 7018 rods with it making the kinds of welds you would typically encounter in the field doing repair work. The model we tested came with four 60-volt, 12-Ah batteries and weighed 54.4 pounds. It's a lot to carry, but still manageable. ESAB says that when equipped with the largest 12-Ah version of these batteries, the machine will melt its way through 33 E6013 electrodes. We didn't burn through that many rods. We ran test beads to get the hang of the machine and then fastened a loop to a weather-beaten steel post at a remote location. It's a remarkable machine with an accessible learning curve suitable for anyone who has stick-welded before.

BEST HAMMER DRILL

DeWalt DCD799 Compact 20-Volt Hammer Drill $89

Decades after DeWalt launched as a line of power tools apart from the radial-arm saw that gave it a start, the brand remains among our highest ranking. We were favorably inclined toward this small hammer drill, among the best we have used in this class of product with a high power-to-weight ratio. The length from the front of its chuck to the back of its motor housing is about 6½ inches. The tool weighs only 2.6 pounds without a battery. With a battery, it's 4 pounds at most. Yet there are many applications in which it can stand in for a full-size drill. That's our take on it after drilling and driving screws in Douglas fir framing lumber, pressure-treated wood, mild steel, and granite. We even drove big 3-inch lag screws with it.

MOST COMPACT BAND SAW

Flex FX2331 24-Volt 2½-Inch Compact Band Saw $269

This is the kid brother of Flex's humongous FX2351 band saw, a brute of a power tool. It's light (8.8 pounds with a 2.5-Ah battery), and its speed control is by a trigger not a dial. We tried it on copper pipe, steel rod, and tubing, and this tool handled all of those with ease. Its cutting depth is 2½ inches, which is still plenty of capacity. If you're on the Flex system and you cut metal, it's a perfect fit for you.

BEST LOCKING PLIERS

Channellock Locking Pliers 102-7, 106-12, 104-10 $19 to $47

It's a fact, not merely opinion, that Channellock makes top-notch hand tools. Can it extend that reputation to locking pliers? We think so. We've tried several of the company's new Spanish-made tools and were impressed with their fit and finish, and that they lock onto a surface with the vicious tenacity that you would expect. All of the pliers feature forged-steel jaws, an extra-long spring-loaded release lever, flawless rivets, and a locknut to set the jaw position. The two-tone paint job makes these pliers look great, but more important is the epoxy resin coating, which provides corrosion resistance. Dirt wipes off easily, too.

BEST TABLE SAW

Bosch GTS15-10 10-Inch Table Saw $649

We ran the Bosch through its paces on 1x white pine, 2x Douglas fir, and 4/4 hard maple, and the machine sawed smoothly and precisely through them all. We're not surprised. We have more than 20 years of experience behind Bosch table saws, going back to the 4000 (it's no longer made). But we tried to not bring a bias, based on prior experience, to our tests. This is a very different machine than previous Bosch saws that we have used. Its saw table is so smooth it can pass for a skating rink, and its rack-and-pinion fence is simple, highly accurate, sturdy, and slides smoothly. We liked the smooth-start feature, which is welcome on a 15-amp power tool and should prevent nuisance trips of circuit breakers. Other features to improve your woodworking experience: 32⅛-inch rip capacity to the right of the blade, and a brake that stops the blade in approximately three seconds when you shut off the saw.

MOST PRECISE WOODWORKING TOOL

Milwaukee 2524-20 12-Volt Power Plane $199

Now this is precision: a power plane that's adjustable in increments of 1/256 of an inch. We're die-hard hand-plane users at *Popular Mechanics*, and although we still see no substitute for a well-honed and adjusted hand tool, this cordless gem comes pretty close. We planed maple and Douglas fir, working face grain, edge grain, and even end grain. Careful adjustment of the cutter (you can't go wrong with such fine increments), a steady hand, and an appropriate speed over the work surface yield a flat and smooth surface without ripple. In terms of weight, it's one of the lightest power tools we've used recently: 4.4 pounds with a 4-Ah battery.

BEST ROTARY HAMMER KIT

Metabo-HPT DH368DD 36-Volt Rotary Hammer Kit $349

Most rotary hammers never touch a piece of granite, but we find the material to be ideal for testing these power tools because the material is so hard (hence the phrase, "hard as a rock"). We chucked a flat chisel, a bull-point chisel, and a ½-inch drill bit into the big green tool. Then we had at the granite test blocks. We were pleased that the drill could score a straight line and break a block fairly neatly along the score line. And putting a hole in granite was about as easy as making a hole in wood. The tool gets high marks from us for power, reasonable weight (8.2 pounds with a 4-Ah battery), and for the fact that it's sold as a complete kit (tool, charger, battery, side handle, depth rod). Even its two-clasp plastic case is sturdy enough for hanging around a construction site where people are busting up granite. As if that weren't enough, when it finished the granite test, it bored dozens of holes in the ancient concrete foundation at our headquarters to inject leak-stopping material. If those tests don't qualify the Metabo-HPT for a Tool Award, I don't know what does.


metabo HPT
MULTI VOLT
Li-ion
36V 18V

BEST TAPE MEASURE

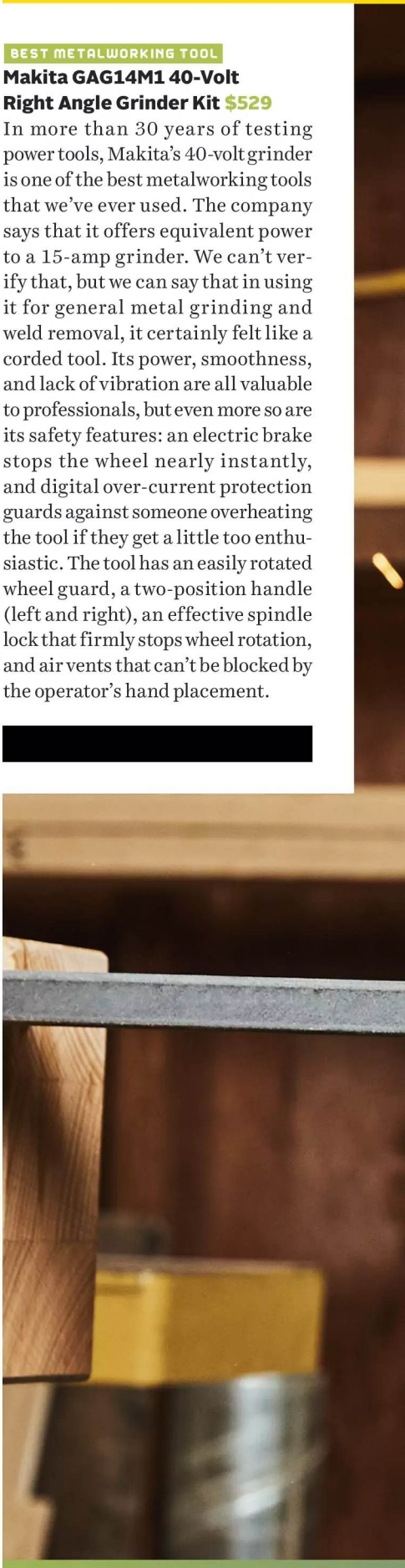
DeWalt DWHT35625S
25-ft. Lighted Tape Measure $70

File this one under "why didn't somebody think of this sooner?" DeWalt's 25-foot tape measure is equipped with a discreetly placed and highly useful LED, located at the tape's front, housed behind a damage-resistant plastic lens. And it better be damage-resistant, because DeWalt rates the tape to be able to withstand a 100-foot drop. We dropped it down a stairwell, without bad effect. That's enough for us. The tape is protected with a heavy rubber coating and its belt clip is removable (most of us just drop the tape into our nail bag anyway). The blade hook is fastened with three rivets (it's very unlikely it will loosen). Dimensions are included on both side of its blade. A USB charge cord is included.

BEST METALWORKING TOOL

Makita GAG14M1 40-Volt
Right Angle Grinder Kit $529

In more than 30 years of testing power tools, Makita's 40-volt grinder is one of the best metalworking tools that we've ever used. The company says that it offers equivalent power to a 15-amp grinder. We can't verify that, but we can say that in using it for general metal grinding and weld removal, it certainly felt like a corded tool. Its power, smoothness, and lack of vibration are all valuable to professionals, but even more so are its safety features: an electric brake stops the wheel nearly instantly, and digital over-current protection guards against someone overheating the tool if they get a little too enthusiastic. The tool has an easily rotated wheel guard, a two-position handle (left and right), an effective spindle lock that firmly stops wheel rotation, and air vents that can't be blocked by the operator's hand placement.




POPULAR MECHANICS
TOOL AWARDS 2024
4-1/2"(Ø115mm)
BL MOTOR
BRAKE

POPULAR MECHANICS TOOL AWARDS 2024

BEST HAMMER

Stiletto Tools Trimbone Trim Hammer $249

The Stiletto Trimbone is a 10-ounce, U.S.-made titanium trim hammer, with a replaceable steel face. It's a beautiful example of toolmaking done right. But don't make the mistake of thinking this expensive tool is too nice or too delicate to use. We grabbed a handful of finish nails and sank one after the other, swinging as quickly and with as much force as if we were framing. The Trimbone is an easy swinger and a reliable sinker. It pulls easily, too, from its straight ripping claw to the nail-pulling slot in the side of its head. It racks up bonus points for its easily replaceable grip: Remove a screw at the base of the handle, then slide the old handle off and the new one on.

LETTO


STANLEY
POWERLOCK
25'
CRAFTSMAN
V SERIES
POPULAR MECHANICS
TOOL AWARDS 2024

BEST TOOL STORAGE

Craftsman CMSTVS6311BK Rolling Tool Cabinet $1,800

Everybody who saw the Craftsman rolling toolbox in our test area wanted it: staff members, visitors, truck drivers making deliveries. And you can see why. It's a beautiful piece of American toolmaking glory, with the heft and authority of a railroad freight car. It's equipped with what seems like acres of drawer space. About those drawers: Each is mounted on a ball-bearing full-extension slide. Each drawer has 150 to 200 pounds of weight-bearing capacity and soft-close sliding action. With spring-supported casters and heavy 16-gauge sheet steel construction, Craftsman rates it as being able to support 3,000 pounds. That's a lot of storage!

TOUGHEST SCREWDRIVERS

Mayhew Tools 27024T 8-Piece Slotted and Phillips Screwdriver Set $79

Hand tools are simple, but it's not easy to make good ones, especially in the United States, where costs are high and obstacles abound. We tried Mayhew's new line of U.S.-made hand tools for driving and removing screws. We clamped various screws in a massive bench vise and applied the screwdriver to it, to see if we'd ream out the screw head or deflect the screwdriver's blade. There was no need for concern with these. They're as tough as they look. Their high-alloy steel blades have a rust-resisting black-oxide finish and are so firmly bonded to the handle that even our hardest, blade-deflecting twist would not loosen them or cause much wear on the blade's tip. The tri-lobe handles provide an exceptional grip and clean easily.

SLIMMEST MULTIMETER

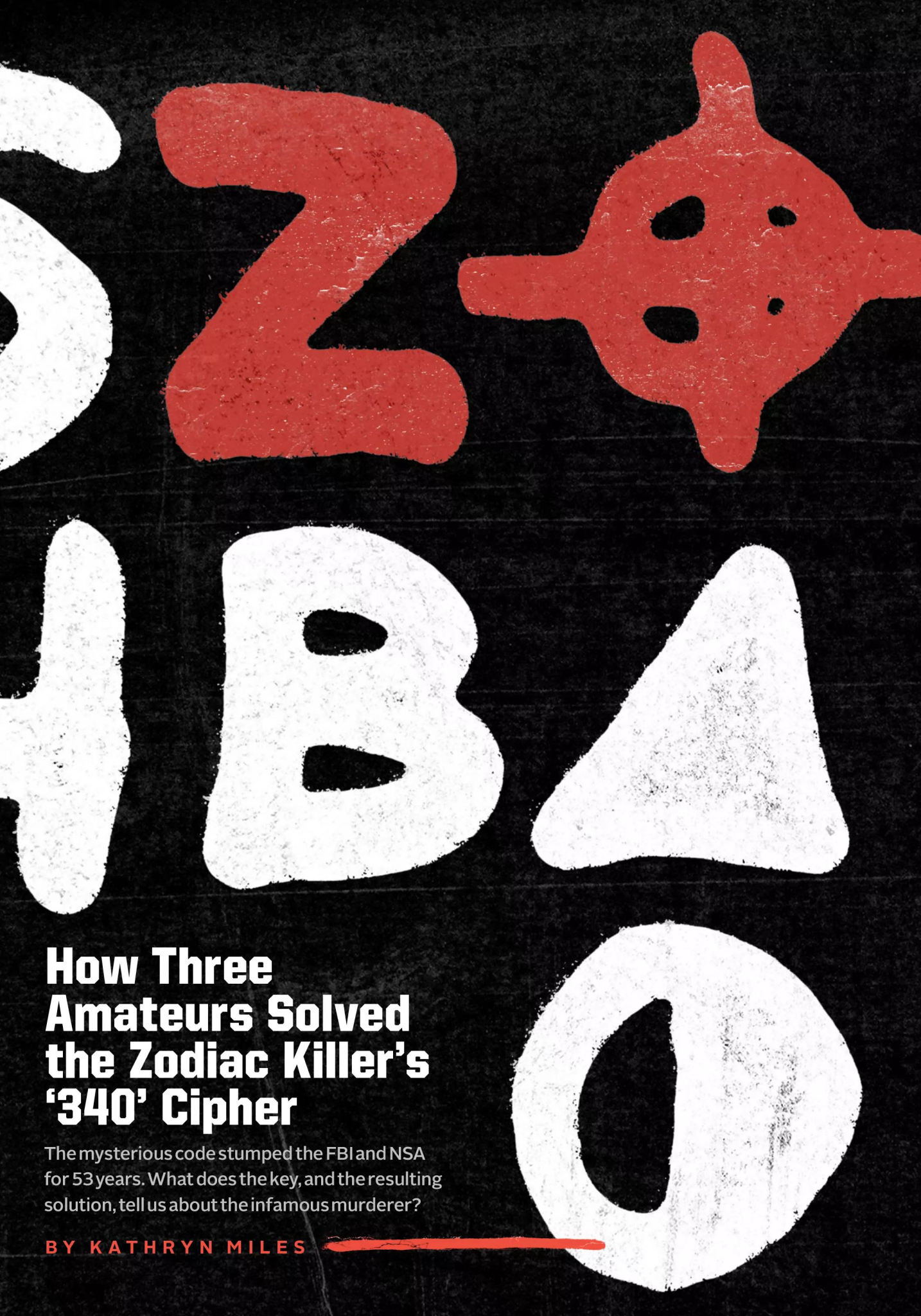
Klein Tools MM450 Slim Digital Multimeter $70

We briefly admired this Klein multimeter before tossing it from eight feet up onto a concrete floor (it's rated for a 6.6-foot drop). Next, we ran a series of electrical tests with it and found it no worse for wear. It racked up bonus points for its slim design (about ½-inch to ¾-inch slimmer, depending on the meter you're comparing it to) and its large face (2 inches by 2 inches). For a meter so slim and light, it's packed with all the features of a full-size meter: AC/DC reading in volts, amps, micro amps, milliamps, minimum and maximum range, and a thermocouple for measuring temperature. Throw in the ability to read hertz, capacitance, and test diodes. The Klein may be small, but you'll be able to get the job done with it.

CLEANEST TRACK SAW

Festool TS60KEB-F-Plus Track Saw, FSK250 Crosscut Guide, FS1400/2-KP Guide Rail $799 (saw), $179 (crosscut guide), $179 (rail)

We're big fans of track saws because they enable fast and precise cuts in sheet materials and solid lumber. That is especially the case when it comes to Festool's newest track saw. It delivers accuracy on par with a small table saw, producing glue-line-quality cuts with the blade 90 degrees to the work surface and at 45 degrees. We used the crosscut guide in similar fashion, making both 90-degree and 45-degree cuts across panels. The Festool was exceptional in all those applications and in one other way: We hooked up a cordless shop vacuum (not even Festool's own machine) and made another series of cuts. The results were nearly dust-free. Impressive. Even more so is that the tool is also equipped with a feedback mechanism that prevents kickback. People have a tendency to overfeed track saws since the only thing you need to do is push them, not guide them. Kickback has been a problem for some users, but Festool solved that problem, and in doing so has produced a saw that cuts safely, neatly, and with incredible accuracy.

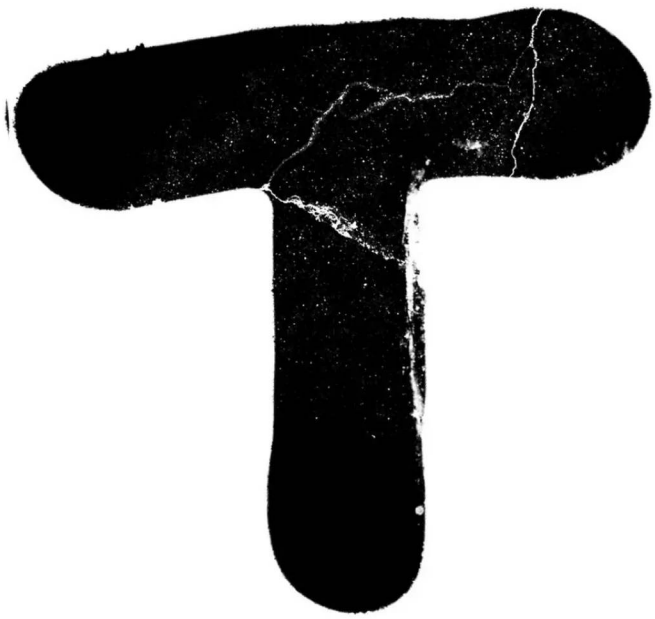


How Three Amateurs Solved the Zodiac Killer's '340' Cipher

The mysterious code stumped the FBI and NSA for 53 years. What does the key, and the resulting solution, tell us about the infamous murderer?

BY KATHRYN MILES


MEDIA



THE ENVELOPE ARRIVED at the *San Francisco Chronicle* in November 1969 without a return address, its directive to the recipient, in handwriting distinctively slanted and words unevenly spaced, to "please rush to editor." The *Chronicle* newsroom had seen the scrawl before, on previous letters sent from the Zodiac, a self-monikered serial killer who threatened to go on a "kill rampage" if the paper didn't publish his writing on its front page. By the time of the November letter, the Zodiac had already attacked seven people, murdering five. His most recent murder—of a San Francisco cab driver, by gunshot—had occurred just four weeks before this new envelope arrived. The Zodiac had mailed the *Chronicle* a piece of the victim's bloodied shirt as evidence of the crime.

The Zodiac's letters were replete with grisly imagery. He signed his "name" with a crosshairs symbol. He shared haunting details of his attacks. He promised to blow up buses of schoolchildren and unleash a "death machine" on San Francisco. But in addition to these overt threats, he included baffling ciphers for investigators to crack, troubling grids of symbols and letters that presumably masked a secret about his identity, intentions, or victims (to this day, the killer has not been found). The Zodiac's first cipher, included in the July 31 letter, had been solved within a week by an amateur husband-and-wife team—but it had only revealed more of the killer's raving. The second, now known as "the 340" due to the number of characters in it, would prove a much more difficult challenge. It came with a letter for the *Chronicle*, reading in part:

PS could you print this new cipher in your frunt page? I get aufully lonely when I am ignored, so lonely I could do my Thing !!!!!!

The paper's editors, along with local law enforcement officials, had no reason to doubt the Zodiac's most recent threat. They published the 340 the next day, hoping it might bring them one step closer to the serial killer's identity, or lead them to his next victims.

But the 340 stumped both amateur and professional cryptographers alike—not just in the weeks following its publication, but for decades. The NSA couldn't crack it. Neither could the Naval Intelligence Office or the FBI. For more than 50 years, the cipher remained an unsolvable enigma, one that grew to almost mythic proportions among codebreakers and cryptography sleuths. Some speculated that the cipher would never be solved—that it was too sophisticated, too challenging for even contemporary cryptographers.

Then, in December 2020, the FBI announced a breakthrough: The 340 cipher had been solved. Not by its crack Cryptanalysis and Racketeering Records Unit, but instead by three computer wonks who'd found one another on an obscure online true-crime discussion board and started collaborating during the early COVID lockdowns. The trio, who had no background in cryptology and no professional codebreaking experience, did what the world's most powerful intelligence organizations could not. On top of the solution's haunting opacity, the intricacies of the cipher itself brought fresh layers of insight that, forensic experts say, might help authorities finally catch up to the killer.

DAVE ORANCHAK HAS always been a puzzle geek. When he's not running ultramarathons near his home in Roanoke, Virginia, the 47-year-old computer programmer spends most of his time working out practical solutions to problems, whether in his coding work or his passion for Shinro, a Japanese derivation of Sudoku. Around 2006, Oranchak became intrigued by the 340's apparent resistance to a solution, thwarting the best efforts of professionals and experts. Tempted by the chance to unlock a slate of notorious cold cases, he started nosing around online discussion boards about the Zodiac. Before he knew it, he was down the rabbit hole, immersed in the Zodiac's story and gaining a reputation as one of the reigning experts on the killer's ciphers.

The Zodiac had a thick case file for amateur

The 340 cipher reached the *San Francisco Chronicle* in November 1969. The killer's first code had been cracked in a week by an amateur husband-and-wife team. Solving this one would require the eventual codebreakers to employ homophonic substitutions, period-19 transposition, the knight's move, and other complex cryptology schemes.

GETTY IMAGES


HAPPY BIRTHDAY!!!
VIRGINIA

sleuths like Oranchak to peruse. Here was a serial killer who had gone out of his way to taunt the police. His handwriting was on file, along with a recording of his voice. Witnesses to his crimes had provided enough information for law enforcement to create a composite sketch of his face. The Zodiac had tallied his victims in marker on the side of a car, drafted homemade ciphers, and mailed scraps of evidence to newspapers. But despite the best efforts of the country's leading intelligence agencies, no one knew who he was. The 340 cipher was one of the final threads to pull, a puzzle with seemingly no discernible rules, schemes, or internal logic.

Oranchak dedicated hundreds of hours to the 340 cipher—"way too many," by his own measure. As his commitment deepened, he became a respected moderator on the Zodiac discussion boards and the leading authority on the 340 itself. He appeared on television documentaries and podcasts dedicated to the Zodiac, eventually giving talks at NSA-sponsored cryptology conferences and sitting on panels with FBI agents actively working in the cryptology field.

The community of amateur Zodiac hunters can be sensationalistic. "There's a lot of chatter and nonsense and arguing about suspects," Oranchak says. But one member of the forums struck him as level-headed and critical: Jarl Van Eycke, a reclusive warehouse worker living in Belgium who had gained respect in the cryptology community after developing his own decryption software program. "Jarl was technically minded, and [he was] approaching the [Zodiac] problem rationally," Oranchak says.

Van Eycke declined an interview request for this story. And he's never spoken on the record about his decryption software or the Zodiac case. Oranchak has never met him; they've corresponded only by email and on forums. Despite Van Eycke's almost total obscurity, he agreed to work with Oranchak on a solution to the 340. That was a pivotal moment that would add speed to the codebreaking process; Van Eycke's software could work through multiple solution sequences simultaneously and provide a rating for the correctness of each result.

Van Eycke and Oranchak began programming the codebreaking software to work through thousands of possible solutions to the 340 cipher.

> "THERE'S NOT A LOT OF RHYME OR REASON TO IT, WHICH MAKES IT IMPRESSIVE THAT ANYONE SOLVED IT."

During the pandemic, Oranchak launched a YouTube channel dedicated to their work from his home office; his family vacation photos and a watercolor portrait of the late family cat, Peabody, looked on as he issued heady primers about cryptology and codebreaking.

Despite the homespun setting, the information in Oranchak's videos was undeniably sophisticated. He used Scrabble tiles to explain substitution keys and anagrams and gave casual lectures on cipher organization strategies such as columnar transposition, in which messages are first written in columns rather than lines. Before long, videos on his channel had millions of views. Oranchak was sure that certain anomalies in the cipher pointed to a logical organizational strategy. While some dismissed the cipher as an impossible exercise from a deranged mind, Oranchak believed that a valuable solution lay behind the inscrutable symbols.

RANCHAK'S BELIEF IN THE 340's logic stemmed from cryptography's foundational principles. Ciphers date back at least 3,000 years. The earliest known cryptogram is from 1500 B.C., when a Mesopotamian potter devised a code to keep his glaze recipe secret from competitors, but methodologies have diversified and proliferated since then. Ancient Spartans and Chinese military leaders used the "scytale" method, writing messages that could only be read when wrapped around a specific rod, and Julius Caesar popularized the substitution cipher, in which

One of the three amateurs who broke the 340 code, David Oranchak did most of his work from his home office, his dog Rosa by his side. He detailed his thought processes and methods on his YouTube channel, where he connected with others attempting to crack the cipher.

PETER MEANS / VTE

"ZODIAC KILLED FOR THRILL. THE CIPHERS ONLY ADDED TO THE THRILL, ONCE THE KILLINGS BECAME ROUTINE."

each letter is replaced by another letter that's a set number of positions away in the alphabet. Sir Francis Bacon favored a "steganographic" approach in which he replaced letters with binaries, and during each of the World Wars, countries used a range of cryptography methods, from simple stencils to the legendary German Enigma machine. All of these cipher varieties employ rotating substitutions that can be "brute forced" by nothing but pencil and paper, says Riad Wahby, PhD, whose research at Carnegie Mellon University focuses on proof systems and cryptography. This quality makes them accessible to the public despite their many layers of complexity.

By the time the Zodiac began his killing rampage in 1968, ciphers and other cryptograms had invaded pulp crime novels and detective magazines. Readers could learn organizational tricks, such as the knight's move or period-19 transposition, and then use them in ciphers of their own. The Zodiac himself likely came of age reading some of those detective magazines and codebooks, says James R. Fitzgerald, a forensic linguist and criminal profiler who spent much of his career at the FBI's Behavioral Analysis Unit. "If Zodiac is ever identified and his house is ever searched, you're going to find dozens and dozens of other codebooks, other pads of paper with other code written on them," he says. "He had an

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Clockwise from top left: The code wheels and lampboard from a WWII-era four-rotor German Enigma machine; the message sent to the *Chronicle* from the Zodiac along with his 340 cipher, taunting authorities and hinting at future crimes; James R. Fitzgerald, an FBI criminal profiler from 1988 to 2007, is a forensic linguist whose work has been integral to the Unabomber, D.C. sniper, and JonBenét Ramsey cases; California schoolteacher Donald G. Harden broke the Zodiac's first cipher sent on July 31, 1969, with his wife, Bettye June Harden.

This is the Zodiac speak
I though you would need a
good laugh before you
hea- the bad news and is
you won't got the can't
news for a while yet do a
PS could you print thing
this new ciphe- with
.on your front page? M!
I get awfully lonely
when I am ignored,
so lonely I could
do my Thing.!!!!!!
Des July Aug
Sept Oct = 7

extended interest in this kind of language usage."

According to Fitzgerald, the Zodiac's schematics align with popular cryptology strategies of the time. The first cipher was simple—a substitution code containing 26 symbols, each of which stood in for a letter in the English alphabet. Donald Harden, a high school teacher, and his wife, Bettye, solved it within a week of its publication. The couple estimates that they spent about 20 hours on the puzzle. They zeroed in on easy-to-find words likely to be used by a murderer; "kill," for example, has repeating letters. Then they followed rules known to any Wheel of Fortune fan: namely, that E is the most used letter in the English language, as are certain letter pairings, such as T-H and Q-U. The solution read, in part:

> I LIKE KILLING BECAUSE IT IS SO MUCH FUN. IT IS MORE FUN THAN KILLING WILD GAME IN THE FOREST BECAUSE MAN IS THE MOST DANGEROUS ANIMAL OF ALL. TO KILL SOMETHING GIVES ME THE MOST THRILLING EXPERIENCE. IT IS EVEN BETTER THAN GETTING YOUR ROCKS OFF WITH A GIRL. THE BEST PART OF IT IS THAT WHEN I DIE I WILL BE REBORN IN PARADICE AND ALL I HAVE KILLED WILL BECOME MY SLAVES.

At first glance, the cipher solution may seem worthless when it comes to catching a serial killer. Not so, says Fitzgerald. Instead, he points to the combination of literary allusion (most notably to Richard Connell's "The Most Dangerous Game") and colloquial sexual boasts as helpful context for a detailed psychological profile of the killer. So, he says, does the deliberate misspelling of "paradise" and the contrived idea of a specific afterlife awaiting the Zodiac.

"He didn't believe any of it," says Fitzgerald of the Zodiac's claims. "Yet it gave him an ostensible rationale behind his killing, so he would not be seen by the public as just randomly and purposelessly choosing his victims."

BEHAVIORAL CRIMINOLOGISTS WHO have worked the Zodiac case surmise that the 340's construction was informed by the ease with which the first cipher was solved—a real blow to the killer's inflated ego. For the 340, the Zodiac increased the number of individual characters to 50 and organized them via a far more complicated cryptogram. The cipher relied upon homophonic substitution, which assigns multiple symbols to a single letter and helps mask common letter pairings. As the cipher's key—cryptology speak for a solution—continued to elude investigators at the FBI and NSA, cryptanalysts began to suspect that the Zodiac had somehow rearranged the order of the symbols, too, possibly including purposeful mistakes in the cipher that would confuse straightforward solutions—"a code within a code," says Fitzgerald. He says the Zodiac, in this respect, fancied himself a kind of criminal mastermind. "The true code writer is very rare, even rarer among serial killers or serial offenders. And the ones that are difficult to break are the rarest of the rare."

The ready solution to the first cipher might have led the killer to overcomplicate the second, including the use of what Fitzgerald calls "false flag mistakes" to throw off codebreakers. "He wanted to become more of an enigma that he already was," Fitzgerald says. "He thrived on that. This guy wanted to put himself above and beyond all those pedestrian-type killers." This egotism might have also informed the Zodiac's moniker, symbol, and costume, which eyewitnesses said resembled that of a medieval executioner. It's also why he seemed to thrive on sending mail to newspapers and demanding airtime from TV programs. On one such show, a man claiming to be the Zodiac phoned in to say that his only worry was eventually being taken to the gas chamber, a fear inconsistent with the killer's supposed megalomaniacal arrogance. Sure enough, the caller was later proved to be a fraud.

The Zodiac affected a persona that not only delighted in taunting authorities, but also became bored with killing and needed to invent games to keep himself amused. The cipher is the primary symbol of the killer's paradoxical needs to be both obsessed about and unknowable. That twisted psychology contributed to its immense difficulty, and is one reason why it took decades to unpack.

AS COVID LOCKDOWNS persisted in 2020, Jarl Van Eycke continued to refine his codebreaking software, AZDecrypt. He reported to Zodiac listserv users that it was becoming faster and more efficient, and he was adding features that allowed users to freeze keywords in the cipher, such as "kill," while running permutations on the other symbols—a process called "cribbing" that can narrow the number of possible combinations a program needs to try. On his YouTube channel, Dave Oranchak theorized that the Zodiac had probably used a combination of schemes in the 340, including the knight's move, in which a message is rearranged in a manner following the moveset of a knight in chess, and period-19 transposition, in which each character is moved 19 positions in the cipher before solving.

That video caught the eye of Sam Blake, a quantitative analysis researcher at the University of

Melbourne. Burned out from his work in computing infrastructure, Blake found Oranchak's channel a more relaxing way to problem solve. He joined the Zodiac hunt with traditional pen and paper at first, but found it "clunky" for interacting with the more complex schemes AZDecrypt was dealing with. Period-19 transposition in particular, he says, "seemed like a pain in the butt."

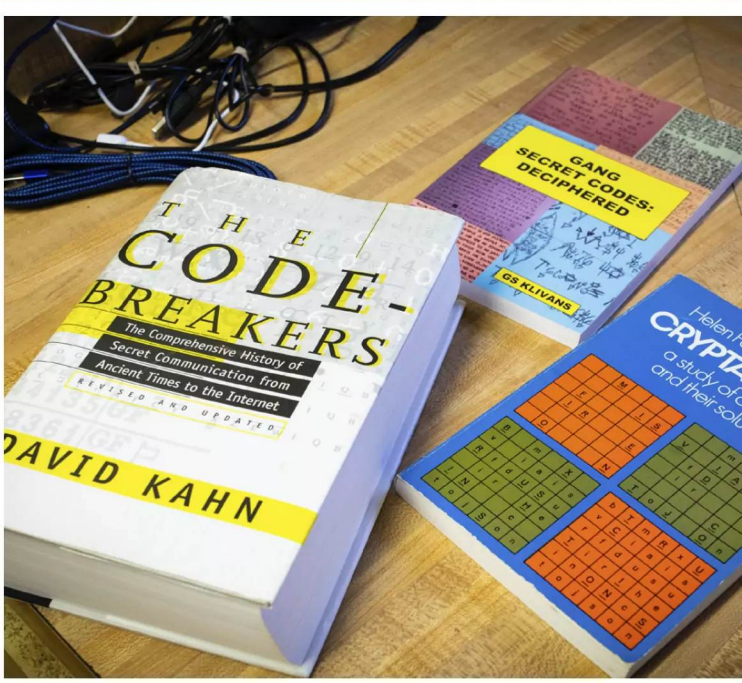
Blake commented on Oranchak's video that it would be easy to enumerate the geometry of period-19 transposition into a computer program, but by that point Oranchak's videos received dozens of comments a day and Blake's mathematical suggestion was lost in the shuffle. But he kept at it until he found Oranchak's email address and proposed his idea directly. Oranchak was impressed, and invited Blake to join him in the hunt for a solution.

Using the University of Melbourne's supercomputer, Spartan, with AZDecrypt, Blake and Oranchak parsed thousands of variations for the 340 cipher. Beyond period-19 transposition and the knight's move, they tried other arrangements, such as alternating the cipher's columns or organizing it along diagonal lines. Each new organization required multiple subvariations, such as moving each character 18 or 20 spaces instead of the traditional 19. It took hours, sometimes days, for AZDecrypt to churn through each possible solution. This would've been impossible in 1969. "Homophonic substitution needs a really robust computer program," says Blake. "I was able to create many different candidate ciphers because I had access to Spartan."

Nevertheless, despite all the programming power at its gates, the cipher didn't yield. Occasionally, AZDecrypt would reveal a single word and compel the codebreakers to dig deeper, but everything led to a dead end. The team began breaking the cipher into sections and applying different solutions to different sections, but even that failed. Months passed. The team soon amassed over 650,000 tested variations, but no answers.

While Oranchak and Blake attacked the cipher, Van Eycke kept improving AZDecrypt. Oranchak wondered if they'd actually tried the right variation already but that it just hadn't been caught by an earlier version of the software. They began rerunning all 650,000 combinations again, with Oranchak hanging out in his wood-paneled office with the family's Labrador, watching the program and waiting for it to produce a viable solution. About halfway through the rerun, he spotted fleeting words and phrases that hadn't turned up during the first pass. In one variation, he found this fragment: *hope you are trying to catch me*. That seemed promising. Then he caught another phrase: *gas chamber*.

Oranchak used AZDecrypt's crib feature to lock in those words, the same phrase the Zodiac impostor had used on TV in 1969, and then continued rerunning the variations. Eventually the program cracked



Materials from Oranchak's collection of cryptography texts. Oranchak, Blake, and Van Eycke combined their skills in programming and mathematics with their interest in traditional cryptography to solve the 340 cipher. Above: After solving the cipher, Oranchak, Blake, and Van Eycke received medals from the FBI's cryptanalysis unit.

PETER MEANS / VTE

Oranchak began working on the 340 in 2006 and posted his first YouTube video about his efforts in April 2020. That first video debunked writer Robert Graysmith's proposed solution to the cipher, and in December that same year, Oranchak released the solution that he helped to obtain. That video has more than two million views to date.

PETER MEANS / VTE

the first section of the cipher. "That's when I fell out of my chair," Oranchak remembers. "I think I scared my dog." The remaining two sections soon followed. They needed to be massaged and corrected in places, but at long last, the Zodiac's message emerged before the codebreaker's eyes:

I HOPE YOU ARE HAVING LOTS OF FUN IN TRYING TO CATCH ME
THAT WASNT ME ON THE TV SHOW WHICH BRINGS UP A POINT ABOUT ME
I AM NOT AFRAID OF THE GAS CHAMBER BECAUSE IT WILL SEND ME TO PARADICE ALL THE SOONER
BECAUSE I NOW HAVE ENOUGH SLAVES TO WORK FOR ME
WHERE EVERYONE ELSE HAS NOTHING WHEN THEY REACH PARADICE
SO THEY ARE AFRAID OF DEATH I AM NOT AFRAID BECAUSE I KNOW THAT MY NEW LIFE IS
LIFE WILL BE AN EASY ONE IN PARADICE
DEATH

MOST EXPERTS, INCLUDING the FBI's crypto unit, agree that Oranchak and his team cracked the 340. Like the first cipher, it reveals a beguiling combination of high and low diction, spelling mistakes, and vague imaginings of immortality. Also like the first cipher, it lacks a hard clue as to the Zodiac's identity.

But James Fitzgerald says that even the 340's variations and mistakes hold valuable information for forensic linguists, including possible hints at the writer's race, ethnicity, age, and gender. Criminals are better at inserting purposeful mistakes than at hiding lifelong linguistic habits. In the case of the 340 cipher, Fitzgerald believes the Zodiac tried to upgrade his language to look more sophisticated than he is, by way of antiquated diction like "all the sooner" and "paradice."

He also suggests that both ciphers contain contraindicators, or statements that represent the

opposite of what is true to the Zodiac. In other words, Fitzgerald asserts that the Zodiac never hunted wild game, never or rarely had sex, and was, in fact, terrified of dying. "Bottom line, Zodiac killed for thrill," he says. "It was mentally, physically, and sexually empowering for him, all of which were missing from his everyday life. The ciphers only added to the thrill, once the killings became routine." Fitzgerald predicts that behavioral scientists at the FBI will glean more information through further study of the ciphers.

Jim Clemente, a former FBI profiler, agrees. "Zodiac is nothing more than a vulnerable narcissist," he says. "He was attempting to show how smart he is [through the ciphers], but he's actually giving us evidence to take him down."

The mechanisms of the 340 itself possibly reveal the Zodiac's limitations as a code writer. The cipher follows a variation of the knight's move and period-19 transposition, but the alterations to each of these schemes are idiosyncratic and sloppy. "We almost didn't find the solution because of them," Oranchak says.

Francis Heaney, a puzzle expert, calls the 340 a "read-my-mind" puzzle. "Basically, [it's when] you've got an idea for a puzzle and there's no way to solve it unless the person has the same idea," Heaney says.

For example, the Zodiac altered his diagonal schematic in a seemingly random manner. He intended the six characters in the center-right of the cipher, which spell out "life is," to be extracted from the diagonal and added to the end of the translated cipher. There's precedent for that; some puzzles have "meta-answers," an extra step after computation to reach the complete puzzle's final conclusion (like when themed crossword clues must be rearranged to solve a riddle). But fair puzzles communicate the need for that extra step through what Heaney calls "breadcrumbs." The Zodiac left no such instructions. "There's not a lot of rhyme or reason to it," Heaney says of the 340. "It's a little bit free-form, which makes it very impressive that anyone solved it."

In his zeal to create a more difficult puzzle, the Zodiac overextended himself and delivered a cipher that was almost impossible to solve—not because of any masterful underlying mechanism, but because the cipher lacked a discernible logic and structure.

The best puzzles build incrementally upon themselves, explains Heaney. They may include multiple steps, but those layers should be iterative. Zodiac's layers were haphazard at best. Solvable puzzles, even challenging ones, hint at their schematics through "flavor text"—proactive hints at a ski slope if, say, the puzzle follows a diagonal pattern. Heaney says inventive puzzlers also build difficulty through focus. The Zodiac sprawled in his methods, shifting the 340 abruptly between simple and homophonic substitution, utilizing multiple transpositions, and inserted a baseless meta answer. Based on the Zodiac's profile, particularly his relentless thirst for attention, he wanted his ciphers to be solved and his message of terror out in the world. These inconsistencies, in that context, constitute a failure.

"IN HIS ZEAL TO CREATE A MORE DIFFICULT PUZZLE, THE ZODIAC DELIVERED A CIPHER ALMOST IMPOSSIBLE TO SOLVE."

Without the computing power of Blake's supercomputer and Van Eycke's AZDecrypt to overpower the Zodiac's unfair schematic, the 340 probably would have remained unsolved. And even though cracking the cipher revealed little biographical information about the killer, Oranchak thinks their methodology can lead to newer, faster ways of enumerating and substituting, which will allow other ciphers to be solved more quickly than under previous methods. "We live in an age of cryptography that is virtually unbreakable," Oranchak says. "But so are these old-school codes." Many unsolved puzzles continue to elude simple solutions, and some of these are connected to crime. "We need a better tool that can figure out what bucket a cipher belongs in before putting all that effort into breaking it."

Cryptological progress, Blake says, will require experts and intelligence agencies to think outside the box, collaborate and crowdsource, and be willing to test methodologies developed by amateurs and armchair detectives. That, says Mike Morford, author of *The Case of the Zodiac Killer*, is the single most exciting aspect of the 340 solution.

"It just proves that if you dig at something long enough and keep at it, whether it's for 40 years, 50 years, there's a chance that you can be part of the solution. These guys proved that," he says. "Their work encourages people to keep digging into these old cases and not to give up." PM

Engineers are still investigating the collapse of **Champlain Towers South in Surfside, Florida,** but early findings shed light on a risk facing poorly constructed residential and office buildings.

BY SOPHIA CHEN

THE CASCADING FAILURES BEHIND ONE OF THE WORST BUILDING

PHOTOGRAPH COURTESY NIST

COLLAPSES

IN U.S. HISTORY

IN THE EARLY MORNING HOURS

on June 24, 2021, a section of Champlain Towers South, a 12-story apartment complex in Surfside, Florida, crumpled to the ground.

Eyewitness accounts and video footage revealed the progression of the condo's collapse. Around 1:15 a.m., a loud crash came from the parking garage beneath the L-shaped structure, as the garage's ceiling, which extended outward to become the building's pool deck, began to disintegrate. Minutes later, Champlain Towers South's eastern wing gave way in two stages—with its midsection falling first, followed by the rest of the wing, seconds later. Dust and debris engulfed the building's west wing, still standing amid a pile of rubble.

Ninety-eight people died in the collapse, and hundreds more lost their homes and possessions. It was one of the deadliest structural building failures in U.S. history, and the emergency response to it was the largest ever in Florida, other than for hurricanes. Before rescue workers even finished identifying the victims, multiple teams of investigators began to dig into the aftermath to determine what led to the building's collapse.

Matthew Fadden, a structural engineer based 20 minutes north of Surfside, learned of the incident later that day. Seeing photos of the wreckage, he noted that the building suffered a "progressive collapse," where an initial structural failure leads to more failures, spreading through the building like cascading dominoes. By September, the court-appointed receiver and insurers for the condo association would hire Fadden's firm, Wiss, Janney, Elstner Associates, Inc., to do its own investigation. Given the scale of destruction, and the fact that Champlain Towers South had been built using common methods, the possibility remained that the deficiency responsible for the building's collapse may also exist at other structures. Investigators felt an urgency to find answers.

Structural engineer Allyn Kilsheimer and his crew, hired by the town of Surfside, which lies 13 miles north of Miami, had begun surveying the debris pile from a distance and speaking to rescue workers the day of the collapse. A team of investigators from the National Institute of Standards and Technology (NIST) joined soon after.

Both Kilsheimer's and the NIST's investigations are still ongoing. But Fadden's team has findings to share. The results of their yearlong investigation suggest the collapse was caused in part by a mechanism engineers call "punching shear failure"—a potentially disastrous risk to some poorly designed or constructed office and residential buildings.

EXPERTS, SUCH AS FADDEN, who point to punching shear failure as a likely cause for the collapse believe the building's design played a role. Champlain Towers South was built using flat-plate construction, a technique that relies on columns to directly support each concrete slab. Each floor resembles a table—a flat surface propped on legs. This contrasts with other construction methods, where horizontal beams support the slab in addition to columns.

Many developers prefer flat-plate construction on residential buildings because it is cost-efficient. Without beams, engineers can reduce the height of each story so that they can squeeze in an extra floor to sell an additional set of condos, says Norbert Delatte, a civil engineer at Oklahoma State University.

Flat-plate architecture also simplifies the temporary wooden structures, known as formwork, that hold the unfinished building up during construction. New concrete is weak when freshly poured and needs extra support from formwork as it hardens, or cures. During the curing process, concrete's major ingredients, such as tricalcium silicate and gypsum, bond with water molecules to form structurally robust chemical compounds. Workers remove the

In the days after the collapse, teams of investigators—like these workers from NIST and U.S. Army Corps of Engineers—rushed to the scene to search for clues.

COURTESY NIST

formwork after the concrete has gained sufficient strength, which they can test by having a lab check portable concrete samples poured on the same day. Formwork, Delatte says, makes up about a third of the cost of a concrete building.

But sometimes efficiency comes with risk. Flat-plate buildings can be more susceptible to punching shear failure.

In a structurally sound flat-plate building, each concrete floor slab bears its weight down on the columns, while the columns react with equal force so that the slab stays put. (Slabs supported using additional horizontal beams, column capitals, or drop panels reduce certain kinds of stresses at the columns.)

But if the column dimensions and slab strength are not calculated properly—say, the column is too small or the slab is too weak—the column can literally punch through the slab. Fadden likens this phenomenon to poking various craft materials with a pen versus a marker: "Putting a pen through a piece of paper is easier than putting a marker through a piece of cardboard." The slab subsequently redistributes its weight to the remaining columns. This added burden may cause the other columns to also punch through the slab. In this way, punching shear at one column can cause

Investigators from the NIST collect cores from Champlain Towers South's pool deck to see how the concrete and reinforcing steel within held up over the course of the building's 40-year life span.

an increase in load to adjacent columns or structural components and trigger an entire building to collapse.

Engineers use a variety of methods to decrease the risk of a column punching through the slab above. They can make the column wider or strengthen the concrete slab, either by making it thicker or by reinforcing it with more steel. Construction workers can also safeguard against punching shear by embedding stud rails, which resemble rows of giant nails, into the concrete slab.

Even at the beginning of their investigation, Fadden's team suspected punching shear failure had played a role in Champlain Towers South's collapse because of the number of columns that had separated from their slabs. "You could see punching-related failures everywhere," he says. Fadden isn't alone. Experts cited in investigations by *The*

"They took a pool deck that was underdesigned from the get-go and added more load to it."

COURTESY NIST

New York Times, *The Washington Post*, *The Tampa Bay Times,* and *The Miami Herald* have also pointed to evidence that punching shear failure contributed to the collapse.

WHEN THE CHAMPLAIN Towers South fell, Delatte, the civil engineer at Oklahoma State University, felt a sense of déjà vu.

Delatte studies historic construction failures. Over the last 25 years, he has compiled accounts of these collapses into a book, titled *Beyond Failure*, which he uses to teach engineering students. He quickly suspected that punching shear failure had undone Champlain Towers South in Surfside and saw an uncanny parallel with several other residential buildings that collapsed because their concrete slabs could not withstand the concentrated force of their supporting columns.

In 1981—the same year the Champlain Towers were completed—Harbour Cay Condominiums, a five-story building situated 200 miles north of Surfside, on Florida's Atlantic Coast, began to collapse as workers poured the concrete for the roof slab of the building. The fifth floor fell onto the fourth, which fell onto the third, and on and on until all five floors lay like a stack of pancakes on the ground. Eleven workers died.

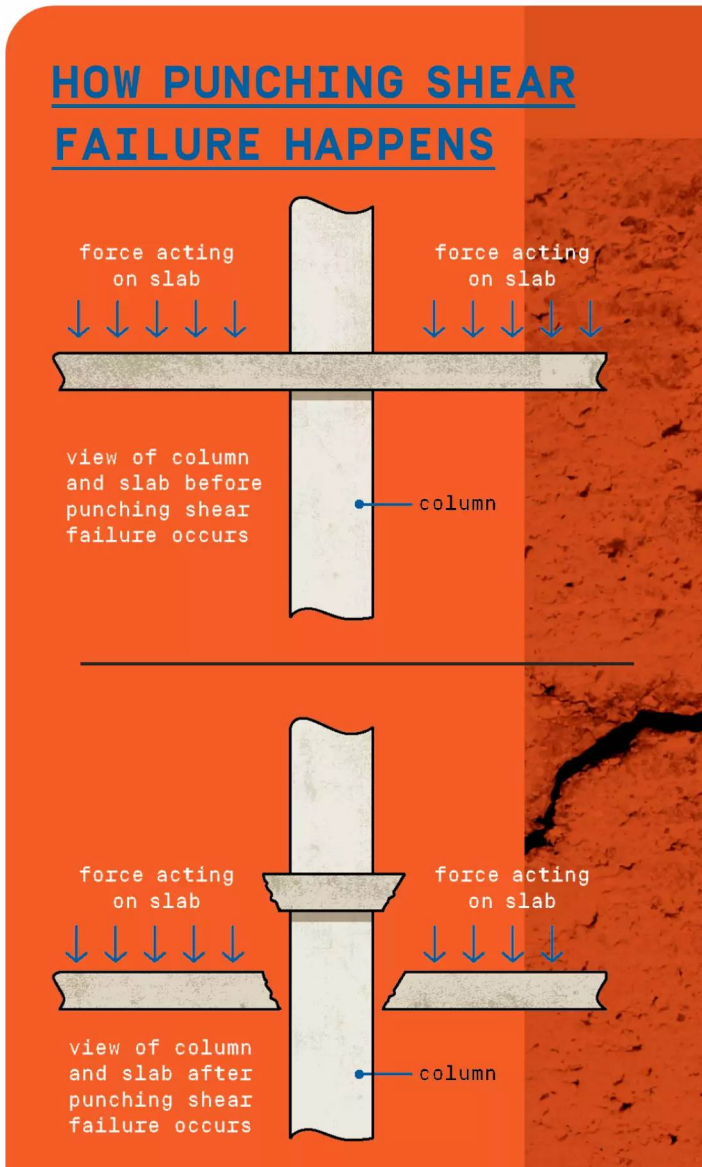
The National Bureau of Standards (NIST's predecessor) concluded in 1982 that Harbour Cay fell due to punching shear failure. The agency found that the building's engineers did not consider punching shear requirements when determining the slab thickness, a key factor that influences the strength of a slab. Harbour Cay's concrete slabs were never strong enough to lie atop their columns. Furthermore, reports stated that the construction workers' premature removal of the building's formwork was a contributing factor in its failure. The building "was held up by the formwork until the formwork was taken away," says Delatte.

A decade earlier, a 16-story apartment building, known as 2000 Commonwealth Avenue, collapsed in Boston, killing four workers. An investigation revealed its formwork had also been dismantled prematurely—the roof slab had not cured to the strength specified by the structural engineer.

Another punching-shear-related collapse in Virginia, about 10 miles southwest of Washington, D.C., destroyed a residential building, killing 14 workers and injuring 34. The building was part of a complex under construction known as Skyline Plaza that included additional apartment buildings, office buildings, a hotel, and a shopping center. On March 2, 1973, the building's vertical midsection collapsed. A failure on the 23rd floor "caused a partial collapse that propagated to the ground," Delatte writes in *Beyond Failure*. The two remaining sections of the building stood like two gapped teeth, sandwiching the rubble.

Throughout construction of Skyline Plaza, also a flat-plate building, its architect and engineer established guidelines requiring the two most freshly laid slabs be supported with formwork to ensure each new slab had enough time to cure to its required strength. But these guidelines never specified how strong the concrete should be when workers removed the formwork. An NBS investigation found that when the building collapsed, the workers had just laid the 24th floor and were in the process of stripping the formwork from the 22nd floor.

Furthermore, Skyline Plaza's concrete slabs may have been even weaker than the team anticipated, due to winter weather. Concrete hardens more slowly in the cold. The 22nd and 23rd floor slabs cured in between 40 and 50 degrees Fahr-



ALYSE MARKEL (ILLUSTRATION)

CSI FOR BUILDINGS

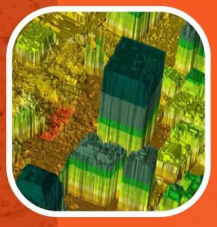
In the aftermath of a collapse, the various involved parties—governments, building owners, insurance companies, contractors—hire forensic engineers like Liberty Janson, former president of the National Academy of Forensic Engineers, to gather evidence about how the building fell.

BLUEPRINTS → Forensic engineers hunt for flaws in the building's original plans, which are often on file with the local government. They may also subpoena the original designers or builders.

CHAINS → Investigators might drag a metal chain over concrete. Janson says changes in the sound the chain makes can reveal whether the top layer of concrete has detached from the rest of a slab.

INFRARED CAMERAS → These imagers can detect temperature differences in a concrete wall, which could point to pockets of water or air that cause structural weakness.

GROUND-PENETRATING RADAR → This device emits radio waves and detects the reflected signal to pinpoint the location of reinforced steel within concrete.



LIDAR → From a helicopter or drone, investigators can use lidar—the same technology some driverless vehicles use to navigate—to bounce light pulses at a structure. By measuring the rate of each pulse's return, engineers can precisely measure the building's position and monitor how it moves over time.

enheit—near the lower limit of the recommended temperature range for concrete curing. The investigators estimated the concrete's strength on those floors was less than half of the specified strength.

UNLIKE THE FAILURES of Harbour Cay Condominiums or Skyline Plaza, where the columns punched through the slabs during construction, Champlain Towers South's columns managed to prop up its slabs for two decades. Fadden concluded that the weakness in Champlain Towers South's floors was primarily the result of improper structural design and misplaced steel reinforcement. Long-term loads exacerbated these flaws to create cracks and deformations in the concrete, ultimately increasing the likelihood of columns punching through. "Concrete is a time-dependent material," says Fadden. "If you put concrete under a lot of load, and expect it to hold for a long time, it will fail eventually."

In their investigation, Fadden's team aimed to find where the failures originated. They pored through architectural drawings, TikTok and security-camera footage of the collapse, previous engineering investigations, and promotional videos real estate agents had used to entice residents to move in. They created computer models of the structure and performed calculations to characterize the strength of its concrete slabs, columns, and beams.

Fadden's investigation pointed to the building's pool-deck slab as a likely point of origin for the collapse. He says that even at the time of construction, it was not built to support the load specified in the design standard. In 1996, contractors added pavers and a sandbed to the pool deck, increasing the weight on the deck. Palm trees that had been added to the deck after construction were later removed, according to a *New York Times* report, because their roots had clogged nearby pipes and led to water damage. "They took a pool deck that was underdesigned from the get-go and added more load to it," says Fadden.

NIST has shared updates over the course of its investigation and has also suggested that the pool deck was, indeed, a weak spot in the building's design. In a statement posted to its website last year, the agency pointed to a series of flaws that weakened the slab-column connections within the pool deck. For one, there weren't enough steel reinforcement bars in the part of the slab that sat atop the columns. Additionally, they discovered that the reinforced steel bars that were there had been placed farther apart than the original design plans had required, thus limiting the slabs' strength.

In 2018, the Champlain Towers South Condominium Association hired the engineering firm Morabito Consultants to inspect the building in

GETTY IMAGES (SIDEBAR PHOTOS)

advance of its 40-year recertification. The firm found "major structural damage" and recommended that the concrete slabs of the pool deck, which lacked adequate waterproofing, be repaired or replaced, among an extensive list of fixes it ultimately estimated would cost $15 million. Two years later, the building's condo association again hired Morabito Consultants, this time to plan and oversee structural repairs. At the time of the collapse, construction workers had begun to repair the building's leaking roof.

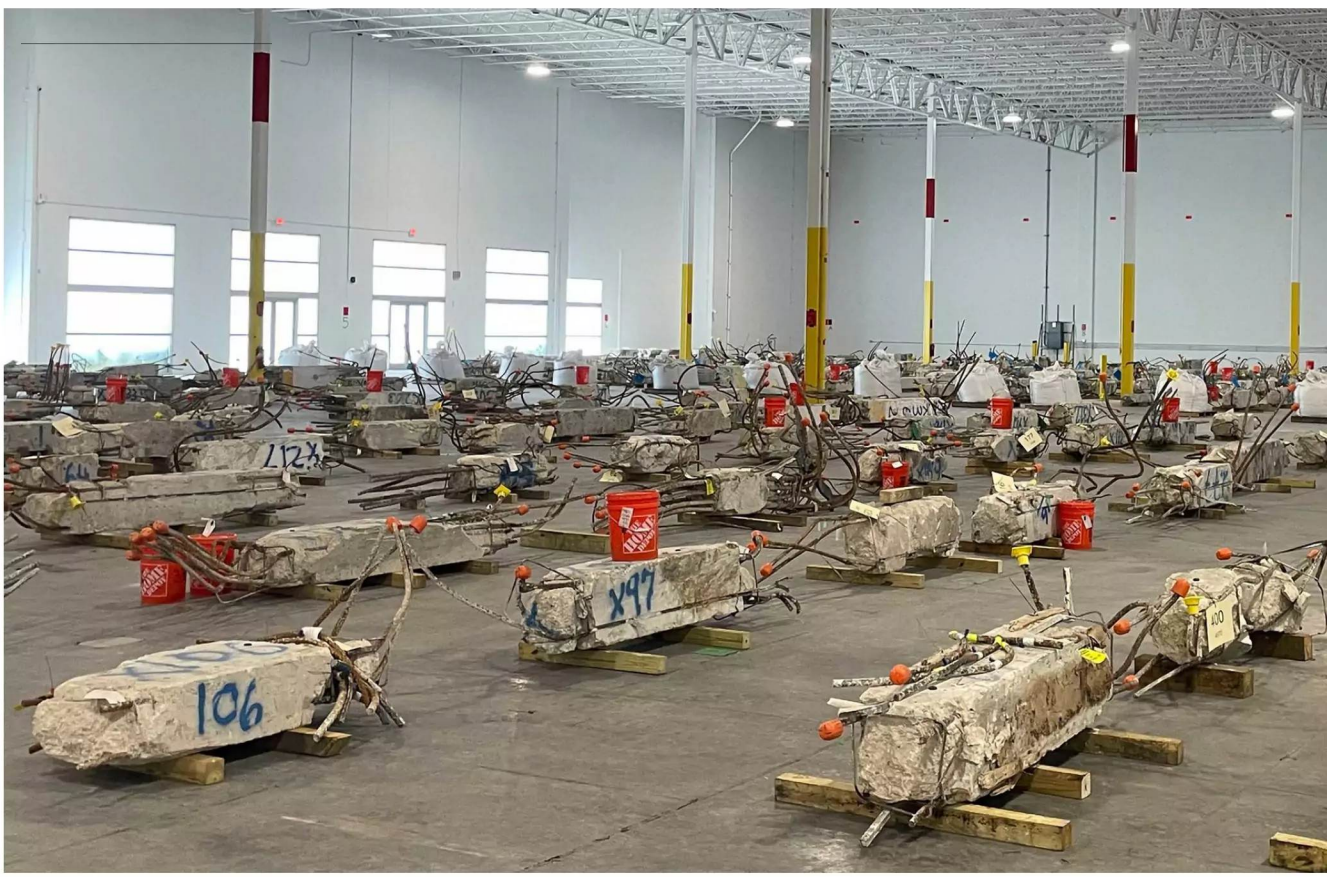
Fadden's team both reviewed documents from Morabito's investigation and performed an independent analysis which showed that the load on the pool deck had significantly exceeded the building code–specified punching shear capacity, a measure of the slab's ability to withstand a concentrated load.

Ultimately, they found several clues supporting punching shear failure as a cause for collapse. One photo the team analyzed from November 13, 2020, shows a column in the parking garage with calcium carbonate deposits on it—a sign that water from the pool deck had flowed through a fracture in the concrete slab from "punching-related distress," says Fadden. In another photo, from June 2, 2021, a part of the pool deck appears to bend significantly due to punching shear distress, causing a nearby planter to crack and slide from its original position. Additional photos revealed large stains around drains on the pool deck, signaling they may not have worked properly. That extra water, his team suspects, further aggravated the risk of failure.

As the pool deck crumbled, it damaged the columns supporting the main building, causing more of it to progressively fail. The collapse stopped at the building's elevator core, which was stiffer and more reinforced than the other parts of the buildings, Fadden says.

THE FAILURE OF CHAMPLAIN TOWERS, along with several other historic collapses, illustrates the risk of punching shear failures in residential buildings. But Fadden emphasizes that such collapses are rare. "There's nothing inherently wrong with flat-plate construction," he says. Nearly all buildings are structurally sound, he explains, and most visible cases of cracks in concrete do not compromise the safety of a building.

Instead, the failure of Champlain Towers South



NIST investigators have collected more than 300 specimens from the site of the collapse—including the columns shown below—spreading them out over two different warehouses for analysis and testing.

COURTESY NIST

Matthew Fadden, Crisol Ortiz, and Alejandra Corona at the site of the collapse. The team spent a year investigating the failure's point of origin.

points to weaknesses in the protocols for evaluating the safety of aging structures. Miami-Dade County law requires buildings to undergo structural and safety inspections every 40 years, known as recertification. But the phrase safety recertification is "extremely problematic," Fadden says, because it lends a veneer of safety that is not backed up by hard evidence.

Fadden points out several missed opportunities over the course of the building's life when an engineer could have recommended reinforcing the pool deck to increase its punching shear capacity. During the repairs in 1996, for instance, "somebody should have found out they should have been repairing the pool deck for punching shear," he explains. And while Morabito Consultants in 2021 developed repair drawings for increasing the bending capacity of the lobby-level deck near the front drive, Fadden says the firm had not developed plans to improve the punching shear resistance of the pool-deck area. (Morabito Consultants released a statement two days after the collapse in which they committed to "working closely with the investigating authorities to understand why the structure failed.")

"We ask ourselves, 'Would I have noticed this issue?' 'Would I have found this?'" Fadden says. "And the answer is, 'I hope so.'"

Because their investigation ended in June 2022, when lawyers for the collapse's victims settled their case, Fadden notes that his team wasn't able to perform structural tests on certain building components. "I actually don't know if anyone will ever have the proof to say, 'This was the reason why this collapsed,'" says Fadden. "But I think the evidence [for punching shear failure] is very strong."

Glenn Bell, NIST's associate lead for the Champlain Towers South investigation, said in a September 23, 2023, statement published on the agency's website that his team hoped to release a final report of their investigation in late 2025. Kilsheimer, who is leading the investigation for the town of Surfside, also isn't ready to share any definitive conclusions. His team is waiting for NIST to give them access to critical debris from the collapsed building, which they will sample and test.

Regardless of the conclusions these investigations reach, Delatte hopes their findings will guide the next generation of engineers and help prevent another devastating loss of life. He intends to include information about Champlain Towers South in his next book and discuss the case with his students, focusing on the high stakes of building construction and maintenance. At Champlain Towers South, the lesson came too late. PM

COURTESY MATTHEW FADDEN

AQUAMAN AND THE LOST KINGDOM

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Cutting the Cord

THE HANDHELD CIRCULAR SAW IS PERHAPS THE MOST VERSATILE power tool for cutting wood. Perfect for a variety of projects, it can be used to cut framing lumber, plywood, and even sheet metal—with the right blade. You'll probably need one at some point, whether you're constructing a shed or treehouse, adding a closet, finishing the basement, or building a workbench.

Originally, handheld circular saws were bulky, corded machines that, at the time, were a huge time-saver for carpenters building homes. With nearly 100 years behind us since those first saws, they have evolved a lot, as have our expectations. If you had to use one of those original circular saws today, you probably wouldn't be a happy camper. Today's saws have dropped bulk, weight, and in many cases, the cord—making them some of the easiest saws to use, ever. So for this installment of The Test, we put three of the top 6½-inch cordless saws through their paces.

HOW WE TESTED

Before testing, we fully charged the saws' batteries, installed the blades, and familiarized ourselves with their features. We used each one to cut 2x4s and 2x6s at 90-degree and 45-degree angles, as well as on a 45-degree bevel. To test each saw's tracking, we followed lines drawn on plywood, cutting long strips without a fence. Finally, to test comparative run times with fresh batteries, we made repeated, full-depth cuts in pressure-treated 4x6s until the batteries gave out, then we tallied up the cuts. We judged the saws on ease of use, tracking, accuracy, and run time.

PHOTOGRAPHY BY THOMAS HENGGE

(1) Milwaukee Fine Finish, (2) Milwaukee Medium Aluminum, (3) DeWalt Framing, (4) Spyder Tarantula Ultra Fine Finish, (5) Diablo Steel Demon, (6) Diablo HardieBlade

SAW BLADES

Handheld circular saws are typically used for cutting framing lumber, like 2x4s, 2x6s, and 2x8s. Each of the saws we tested here came with framing blades, but there are blades for nearly any material you can imagine cutting. Generally speaking, blades with more teeth will make a cleaner cut in wood and leave fewer saw marks. Framing blades will typically have a lower tooth count, around 18 to 24, and make a rougher cut because framing is typically hidden behind drywall. Blades for cuts in wood that will be exposed have higher tooth counts of 40 or more. And blades for metal will have 54 or more teeth. To make the most of your saw, be sure to match your blade to the material you need to cut.

Run Times

Each of the models tested comes with a 5.0-Ah battery, so we ran them head-to-head, cutting full depth into heavy, wet, pressure-treated lumber. While not exactly a run-time test, counting the cuts showed how much work the saws can do on a single charge.

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BEST OF THE TEST

FLEX 6½-INCH IN-LINE

★★★★½

Price: $250 | **Power:** 24-volt
Battery: 5 Ah | **RPM:** 5,500
Max cut depth: 2 9/16 in.
Max bevel: 47° | **Blade:** Framing, 24t
Weight: 9.4 lb

The Flex differs from other saws with its handle oriented in-line—on the same plane as the blade. Plus, the saw motor is behind the blade, which is driven by a belt. This makes the saw much narrower and able to be used in tighter places. It's also easier to use against a makeshift fence, which is helpful if you're cutting plywood. We were impressed by the Flex's battery life, which was longer than for other saws tested. The blade guard spring tension took some effort to overcome when starting a cut—we occasionally had to hold smaller pieces to prevent them from moving. The Flex has a port that rotates 270 degrees to direct sawdust in any direction, as well as to connect to a shop vac. Considering price and battery life, the Flex In-Line is a remarkable value.

MILWAUKEE M18 FUEL 6½-inch

★★★★★

Price: $320 | **Power:** 18-volt
Battery: 5 Ah | **RPM:** 5,000
Max cut depth: 2 3/16 in.
Max bevel: 50° | **Blade:** Framing, 24t
Weight: 8.4 lb

Milwaukee's M18 Fuel circular saw was an absolute pleasure to use, doing everything we asked of it well. We found it glided across plywood easily, tracking straight down lines drawn on it, with little effort or deviation. While the bevel gauge was no more accurate than the others tested, its clear, sharp markings were easier to read and make adjustments quickly. The Milwaukee's blade guard has no provision for dust collection, but it efficiently sent sawdust straight down, behind the blade—with fewer visible particles flying elsewhere. We had no trouble staying on our cut lines with the M18's brilliant LED that shines forward, in the direction of the cut. The 24-tooth framing blade allowed us to make remarkably clean cuts with very few saw marks in the face of the cut.

DEWALT 20V MAX XR 6½-inch

★★★★☆

Price: $300 | **Power:** 20-volt
Battery: 5 Ah | **RPM:** 4,950
Max cut depth: 2¼ in.
Max bevel: 50° | **Blade:** Framing, 18t
Weight: 7.6 lb

The DeWalt 20V Max XR was the lightest saw we tested, by a significant ¾ pound. It's also the most compact saw in the test—shorter front-to-back and top-to-bottom. We found the spindle lock the most accessible of the saws tested, making blade changes easier. Regarding blades, the Max XR comes equipped with an 18-tooth framing blade, which is coarser than the others tested. This may have accounted for the large amount of sawdust it sent airborne. It does come with a snap-on ejection port to connect to a shop vac or dust collector, which helps cut down on debris. The saw uses simple cam levers to lock adjustments for both cut depth and bevel—we found both were easy and quick to adjust and held fast.

4

Editors' Choice

// ONE PIECE OF GEAR THAT'S WON THE HEARTS OF OUR TEST TEAM //

POPULAR MECHANICS EDITORS' CHOICE

Restor-A-Finish | $10

I love to build furniture, but I don't particularly care for refinishing the old stuff. It's messy and it takes a lot of time to do it well. I've had something of a change of heart since finding Restor-A-Finish. Everybody I've talked to who has used the stuff—they are many—loves it. And it's easy to see why: It's a shortcut and the least invasive way I know to rejuvenate a tired piece of furniture.

Using it is about as simple as this work can get. Pour a little directly onto the surface that needs rejuvenation and spread it around with a soft cloth, working it in thoroughly but gently. Wipe up the excess and let the surface dry. For furniture that is badly scratched or faded, use 0000 steel wool.

Restor-A-Finish consists of solvents and wood stain and comes in various hues, such as maple, oak, and mahogany. When you use it, you're partially dissolving the old top layer of finish and reconstituting it with a slight shift in its color. Note: It does contain old-school solvents such as acetone, so wear a respirator and use it in a well-ventilated place.

I've used Restor-A-Finish on a mid-century veneered coffee table, a 1940s (war surplus) oak office desk, an early 1900s chest of drawers, a series of folding card tables, and some 1960s bedroom furniture. I even used it to shine up two oak bathroom vanities, both of which are 23 years old. Everything came out looking great.—*Roy Berendsohn*

PHOTOGRAPH BY THOMAS HENGGE

Garden on Wheels

IF YOUR SHOP is equipped with power tools, the flower cart probably won't take more than an evening's time to construct

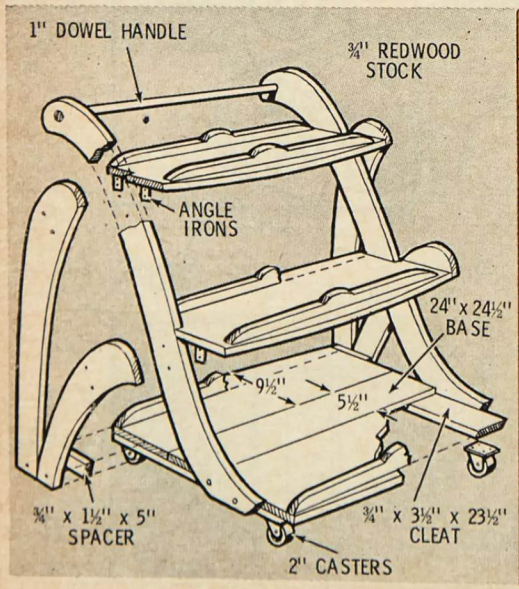
FLOWERS ADD a bright spot to any room but it's usually inconvenient to move them around to catch the sun or to lend cheer to another part of the room.

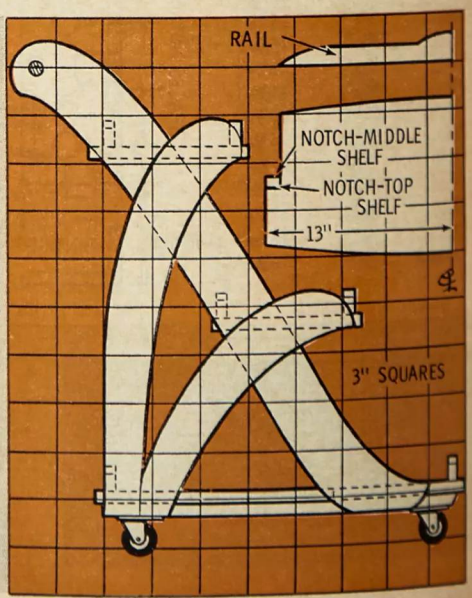
The gracefully designed cart shown here makes it easy to show off your indoor garden to best advantage—and it's an attractive piece of furniture besides.

Solid stock, ¾-in. thick, is used throughout. Redwood is especially suitable for this project, particularly when finished with a couple of coats of marine spar varnish.

Begin work by laying out a full-size pattern for the sides. Half-patterns are sufficient for the shelves and railings, as indicated in the grid drawing below. After transferring the pattern to the side pieces, tack the corresponding side members together through the waste portion so that when band-sawed, both pieces will be identical in shape.

When assembling the pieces, first join the curved outside members to the handle sections. Next, attach the baseboards with wood screws. Then insert the dowel handle and join the sides to the bottom. Finally, position the railings and attach with glue and screws.—*Roberta L. Fairall*





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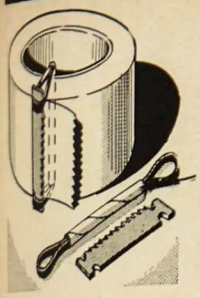
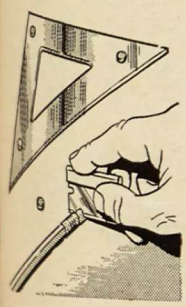
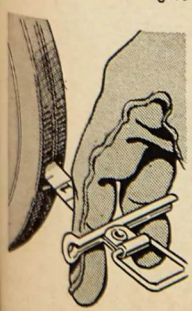


STRAIGHT EDGE for tearing masking tape is made by notching the ends of a short length of hacksaw blade and mounting it on tape roll with short rubber band inside a soda-straw roller



SKIDPROOF FEET for an artist's triangle will prevent it from slipping off the board. Cut thin slices of rubber from a pencil eraser and cement them to the triangle where indicated

WHEN WORKING outdoors in cold weather, you'll find that a measuring tape will be much easier to hold if you slip a cotter pin over the end to serve as a bar grip for your fingers



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