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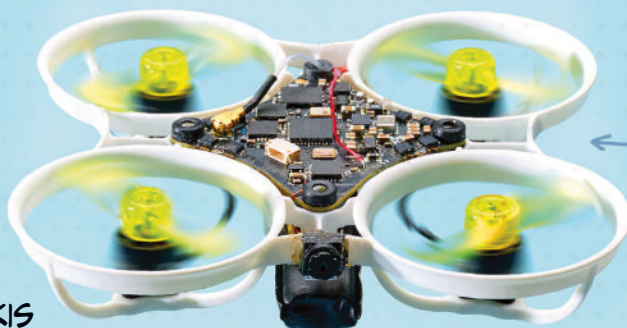
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Photos: Mark Madeo and Saul Griffith

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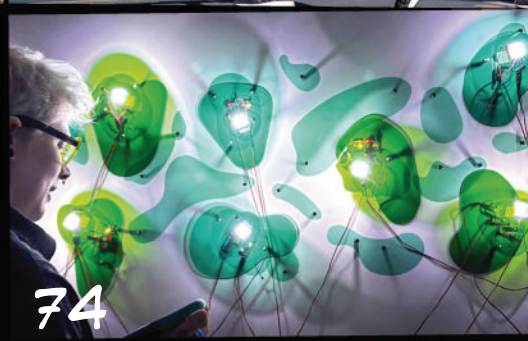
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*What's the closest call
you had to catastrophe
during a build?*



Kati
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(A Device of One's Own)
Confirmed a component's
voltage rating by adding
the magic smoke.
Twice, just to be sure.



Ryan Cho
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Nearly lost an eye to
a rotary tool wheel
exploding. Always wear
eye protection.



Scott Stephenson
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(The Lightest Whoop)
Forgetting to switch on
my R/C controller sent
my 450 helicopter build
into the ceiling, narrowly
missing my head.

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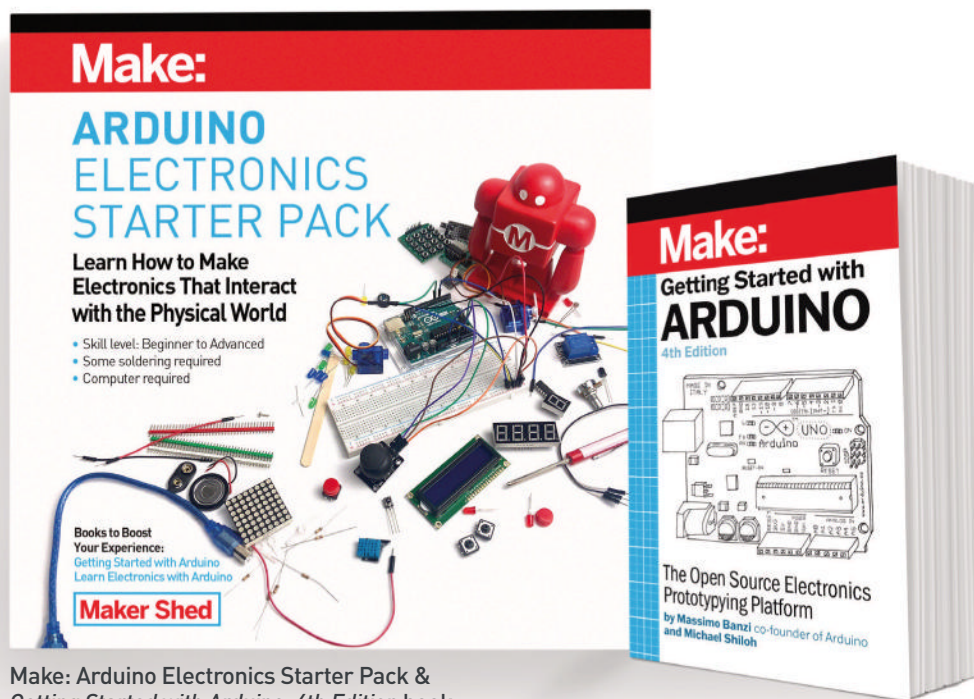
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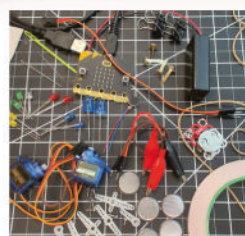
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FROM THE EDITOR'S DESK



THE MAKER MOVEMENT: A TIMELINE

The Maker Movement is a global cultural shift celebrating creativity, innovation, and hands-on learning. Rooted in the DIY culture of the mid-20th century, it gained momentum in the early 2000s with the advent of digital fabrication tools, open-source platforms, and collaborative communities. From garage workshops to the White House, from the first Maker Faire to a pandemic-era PPE response, this timeline traces the movement's remarkable journey.

For this year's opening of the East Bay Makers Club in Berkeley, California (see page 7), our team put together a timeline of the Maker Movement as a large poster for a wall in the new makerspace. Credit to Gillian Mutti for the text and Juliann Brown for the design.

Subscribe to our Substack newsletter to see the full timeline at makezine.substack.com/p/the-maker-movement-a-timeline.

Substack user Kacper responded: The timeline is a good reminder that the maker movement never actually needed permission from anyone. That's the part I keep relearning the hard way: build the thing first, then find out if it matters to someone else. —Kacper Strzelczuk, Zambrów, Poland

FAMILY TRADITION

My father was a carpenter of Midwest and Ozark culture. He taught me this technique [Yakisugi charred wood finish, "Torch It," *Make: Volume 97*] without giving it a name. We used it for making staffs and walking sticks. When used on green saplings the fire hardened the outer layer but sealed the inner sap to maintain flexibility. Like quenching a katana.

Francis (Fran) Herin died peacefully at home on May 27. He was 84 years old and a maker in his own right. Those memories are more powerful than ever. —Scott Herin, Wentzville, Missouri 🍷

MAKE AMENDS

- In *Make: Volume 97*, the photos of Devising Delight at Emerald City Comic Con, on the cover and in "Inspirational Inflatables" (page 50), are by Marshall Haque/Visual Shotz.
- In our Toolbox review of Cytrence's Kiwi+ (Volume 97, page 127) we labeled it a KVM (kernel-based virtual machine) when in fact it's a KVM (keyboard/video/mouse) for headless Raspberry Pi projects. Enjoy the corrected review on page 123 of this issue.

Welcome ...

A Tale of Two Makerspaces

by Dale Dougherty, President of Make: Community

A Pew Research poll shows that 60% of American adults feel less happy today than they were in the previous decade. The Surgeon General has declared an epidemic of loneliness and isolation. One researcher, Dr. Jean M. Twenge, writes about “the rise of digital media and the fall of everything else” and suggests that “Americans are less happy due to fundamental shifts in how they spend their leisure time.” We are spending more time on devices and less time interacting with people in the real world.

On the Fourth of July weekend, I was part of a grand opening ceremony for the East Bay Makers Club in Berkeley (pictured below). The co-founders of this new community makerspace, John Boiles and Joe Taylor, had been organizing build nights in their homes, creating time and space to build things together. Both have engineering jobs in tech by day: John at OpenAI and Joe at Lyft. Regardless of what they do for work, they both enjoy building and making things. John had reached out to me 15 years ago about his beat-up Oldsmobile that he could control remotely with his iPhone. Joe likes to refurbish pinball machines and he’s working on a modular pinball construction system.

The two of them expanded their build nights to include friends, then decided to create a space for the community. When OpenAI went public, John was able to use some of his stock to provide funding for this new makerspace. Addressing the 100 or so people that gathered that evening, John said: “The East Bay Makers Club encourages people to build things because building things is awesome.” Judging from the enthusiasm of those who showed up, I expect that many will want to join this local community of makers.

Across the Bay in San Francisco, Humanmade is a fairly impressive makerspace that opened in a new location last year. Created by Ryan Spurlock and other ex-TechShop employees, Humanmade’s mission is to offer workforce training and to incubate future hardware businesses. In June, I attended the kickoff of their 2026 hardware accelerator, a program that

was funded through a grant from the State of California.

Twelve individuals or teams presented the projects they were working on. They were grateful to be accepted into the program and to learn from each other. They needed access to the makerspace to work on their hardware prototypes. Few of these projects were based on AI; most tried to solve practical problems. One participant said it’s daunting to be doing a non-AI startup in San Francisco, where every billboard is an advertisement for an AI company. Many were graduates of Stanford or UC Berkeley, while others had worked in large companies and believed it was time to do a startup of their own. They were doing what they wanted to do.

This tale of two makerspaces, despite uncertainty about the future and AI, shows that we might be living, as Dickens wrote, in the best of times and the worst of times. Makerspaces are bringing people together to work on meaningful projects and tap into the expertise and enthusiasm of other makers. If these spaces thrive, so will we.

Makers are active, engaged, optimistic — and happy. “Aristotle believed that true happiness is found in action,” said writer James McPherson in a conversation with me. “It is not about comfort but activity.” This issue of *Make:* is all about action, perhaps in a different sense, with lots of projects that are fun to build and get you outside, together in real life, and off digital media. 🍷



John Boiles

DIY HACKERSPACES ELECTRONIC ROCKS
SOLAR CIRCUITS CRAFTS SUSTAINABILITY CORE ZERO ALTERNATIVE ENERGY VEHICLES
YOUNG MAKERS TOYS LIGHTS
LEARNING ART CARS HARDWARE BIOLOGY CERAMICS GAMES JEWELRY SOLID STATE

MADE ON EARTH



Amazing builds from around the globe

Know a project that would be perfect for Made on Earth? Let us know: editor@makezine.com

INSTAGRAM.COM/OFFICE.OF.COLLECTING

Oreck's Office of Collecting and Design (OCD) began in 2020 as an extension of her animation studio in Las Vegas, where she'd worked as a stop motion animator and prop builder. "Initially, the museum was just going to be a luscious and cozy prop library," she says. But having spent more than a decade at the American Museum of Natural History, creating her own museum was a natural next step. Her longest-running collection is of "unplayable" dice: too old to roll in a Vegas casino due to chipped corners, uneven pips, or poor balance. The collection now has hundreds of the curious cubes, in assorted sizes, colors, and unusual markings.

Oreck describes her collecting philosophy as deeply intuitive. “The objects sometimes have their own voice, certainly their own personality,” she explains, “an ineffable weight that dictates where they belong.” She’s drawn specifically to what she calls the “residue of attention” — the forgotten silt of other people’s lives, items that drift to the bottom of the junk drawer across generations.

Visitors to the traveling collection can explore the treasures, assemble their own “flatlay” (a photographic souvenir of personally curated objects arranged just so), and even take a few trinkets home from the gift shop.

Look for Jessica and her traveling museum near you. Can't make a tour stop? Oreck's Treasure Club, Postcard Club, and Decoder Club bring the magic directly to you. To browse the collection, join a club, or find the tour schedule, visit officeofcollecting.com. —*Bob Knetzger*



MADE ON EARTH



FUTURE SIGHT [INSTAGRAM.COM/LULU_PAWTECH](https://www.instagram.com/lulu_pawtech)

At first glance, the helmet may look impossible — like a piece of armor from a futuristic video game, or the mark of a comic book superhero. There are no visible eye slits, no tinted visor, no obvious signs that suggest a human being could see out of it at all. And yet, pseudonymous maker **Lulu Pawtech's** ingenuity has combined form and function into something straight out of science fiction.

The idea first arose when Pawtech was helping his partner, Lulu Furs, design a head-mounting system for her cosplay suit. “We started thinking about how to get around the limitations of where the eyes are usually positioned,” he recounted. “The second half of the idea came from VR headsets ... they have that passthrough mode where the inside displays what the outside cameras see. Those two ideas kind of clicked together, and that’s how the concept was born.”

After designing the helmet in SolidWorks, Pawtech 3D printed its main structure in CF-polycarbonate, while the smaller detailed parts are SLA resin — red transparent for the glowing bits (assisted by red backlights), and simple

white for everything else. Pawtech counts 177 printed parts in total, and the shell panels are magnetically attached for easy maintenance or a cool half-assembled look. Video passthrough sight, meanwhile, is maintained by two cameras mounted on the sides to provide stereo vision, with screens inside for each eye, a 4-hour battery life, and ventilation fans with moving shutters.

For Pawtech, the finished helmet is the culmination of 4 months of from-scratch making. “There were many moments during this project when I genuinely had no idea what to do next, because I needed to learn so many new things,” he said. Even now he is dealing with issues related to the helmet’s limited internal space. And yet he wouldn’t have it any other way. “I had no background in engineering, programming, machining, electronics, or anything,” he says. “But if your whole life is just routine, you slowly start to decline. You need to keep learning something. Otherwise, you stop feeling like a living person and start feeling like a machine.”

—Marshall Piros



Lulu Pawtech



TREES, TRANSISTORS, AND TIME STEVE-PARKER.NET/FUNERAL

By any reasonable logic, a dead tree becomes lumber, mulch, or firewood; perhaps a chair or ship in skilled hands. When a live oak slowly succumbed to fungal oak wilt in **Steve Parker's** yard in Austin, Texas, he decoded it — giving it a voice and letting us “hear what’s already there.”

His sprawling installation *Funeral for a Tree*, housed at Austin’s Ivester Contemporary gallery, is certainly more than the sum of its (many) parts. Less a single object than a network of interconnected machines translating physical material into sound.

The labyrinthine assemblage has the hypnotic quality of a dirge played by a Rube Goldberg machine. Layered, instrumental, and kinetic, the sculpture is built from the tree itself and a collection of unlikely collaborators: salvaged brass instruments, discarded *shengs* (a Chinese mouth organ), plumbing hardware, and strategically placed ventilators and CPAP machines that let the piece breathe.

The project is packed with clever mechanisms. A servo-driven camshaft animates a tree branch to strike a wind chime in a hocket arrangement,

in which a single melody is split between alternating voices to create an offset, interlocking sound. A bass drum serves as a visualization system where sawdust and birdseed dance to low-frequency playback, while Arduino-controlled timing systems coordinate sound, motion, and airflow from the varied medical devices that breathe within the installation.

The centerpiece of the project is a series of records or “wood cookies” sliced from the tree’s trunk into cross-sections into which Parker CNC-routed spiral grooves as if encoding audio on vinyl. The discs spin on custom-built, wood-on-wood turntables, needle included (in some cases, a literal toothpick).

“Each slice is encoded with the sounds of migratory birds that would have roosted in the tree over its lifetime,” Parker explains. Yet these aren’t archival recordings, but reconstructed bird songs interpreted on the sheng by Taiwanese virtuoso Jipo Yang. The tree doesn’t just memorialize loss — it performs it. An elegy, in memoriam and outside time.

—Jennifer Blakeslee



MAKING IN MIAMI

A decade-long journey of connecting makers of all ages and abilities with opportunities to build a better future

Written by Tom & Daisy Pupo



TOM & DAISY PUPO are the husband-and-wife co-founders of Moonlighter FabLab, a nonprofit FabLab in Miami Beach with a mission to connect making and learning with social impact opportunities. Learn more at moonlighterfablab.org.

We started Moonlighter 10 years ago, fresh out of architecture school, with a vision to build a space where community-driven design and engineering could take on the big challenges of the next generation. Since then, we've partnered with Fairchild Tropical Botanic Garden and NASA. We've worked with MakerEd to train teachers in maker-centered pedagogy, and with *Make*: every year as co-producers of Maker Faire Miami. Through a partnership with the City of Miami Beach, Moonlighter serves as a cultural anchor for STEAM enrichment in local schools while operating the STEAM learning center and membership-based community FabLab in the heart of South Beach.

Our approach was informed by the realization that the greatest eras of human progress were built by curious people, obsessed with understanding how things worked and driven to make them better. When we see a teenager prototype a solution to a real neighborhood problem, or an adult learner walk into a new career with confidence and belonging, that's what we built Moonlighter for.

Moonlighter is one FabLab in one city. But the model we're building, rooted in education, workforce development, civic engagement, and open access, is an argument for what every community deserves.



Photos by Jadayne Smith; bio photo by Nathanael Filbert

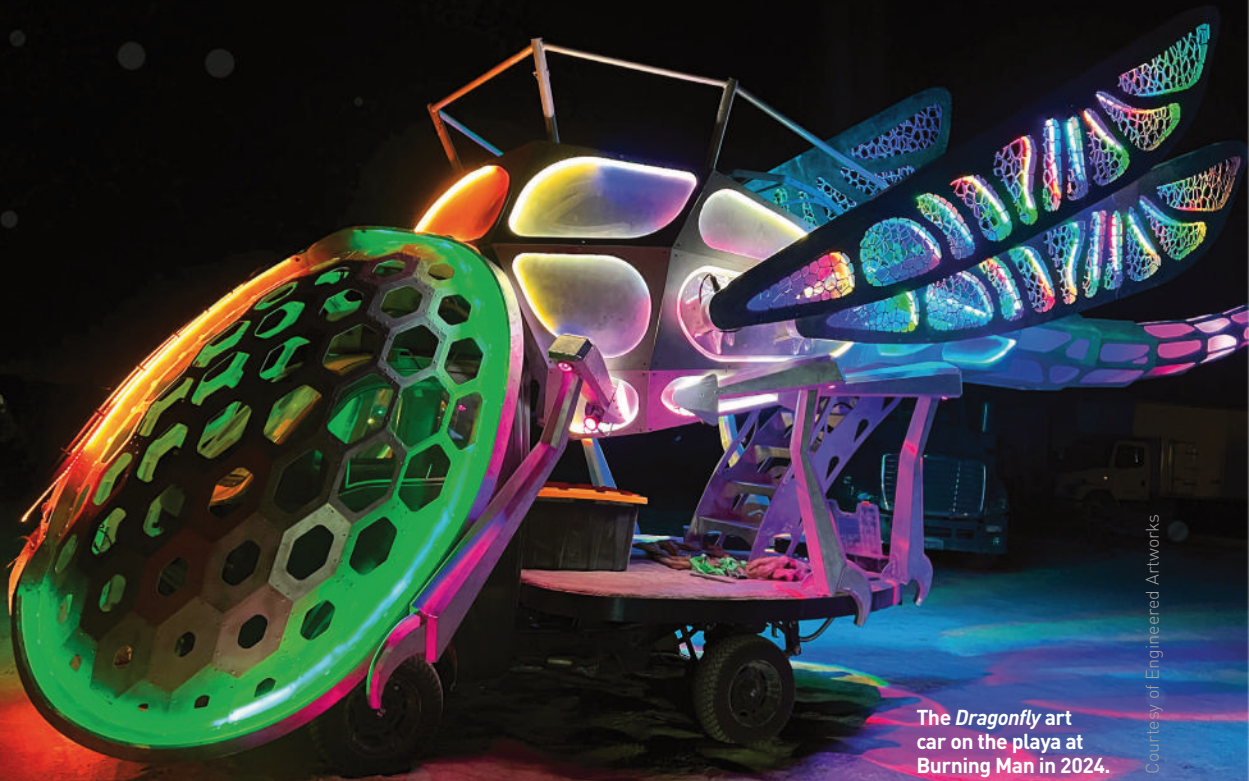
- 1 Dewalt 10" miter saw
- 2 Ryobi power tools, under the "Imagine" sign. John Lennon would be proud.
- 3 Rikon band saw
- 4 Jet oscillating belt sander
- 5 SawStop table saw, operated by member Isabella Dotres. We love this machine, why did we use contractor table saws for sooooo long before?
- 6 Sheet material storage. Fun fact: This was the first custom fabrication job we gave our FabLab manager, Augusto Vanegas, to build!
- 7 Drop-down electrical extensions. No more "Where can I find an outlet?"
- 8 Bauer dust collector
- 9 Ryobi router table
- 10 Tikkun Olam Makers Global Toddler Mobility Kit, made collaboratively at Maker Faire Miami 2025
- 11 CNC furniture prototype, the first chair Tom ever designed. It's not very comfortable!
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- 14 Display system made with Maker Pipe connectors
- 15 Custom-built monoplane, built by one of our mentors and supporters, Daniel Rodriguez
- 16 Custom-fabricated BMO from *Adventure Time*, with built-in video game emulator, built by one of our directors, Mario the Maker
- 17 3D printed Yoda prop. We have some great friends at the 501st Legion!
- 18 Custom hardwood skateboards, by original member Drip Drop Boards
- 19 3D printed zoetrope sculpture replica by John Edmark. We made this for an interactive event at the Frost Museum of Science.
- 20 Electronics component library — so many components and microcontrollers, sticky notes to recategorize sections!
- 21 Electronics workbench: Weller iron, heat gun, Siglent oscilloscope and power supply, and vintage Bantam PCB mills (amazing machines!)
- 22 3D printed Mythosaur plaque from *The Mandalorian*.

FEATURES: Dragonfly Art Car

THE ANATOMY OF an ART CAR

HOW THE PROS BUILD STUNNING RIDES
TO CRUISE BURNING MAN AND BEYOND

WRITTEN BY DALE DOUGHERTY



The *Dragonfly* art car on the playa at Burning Man in 2024.

Courtesy of Engineered Artworks

There is an art to making “art cars” for Burning Man, and Sean Orlando and his team at Engineered Artworks in Richmond, California, are masters after building 15 of them. As the name implies, the creation of an art car requires engineering and design but also inspiration and artistry. It should create a satisfying ride for the driver and a safe, fun ride for its passengers on the playa. Which is all to say, an art car has to work well, and it has to “wow.”

A graduate in art from UC Berkeley, Sean and many of his collaborators worked for years at places like American Steel Studios in West Oakland, before moving to Richmond in October 2021 to open Seaport Studios. It’s a big warehouse divided into small spaces that he rents to local artisans and is also the home base for Engineered Artworks.

Out back, there’s a big paved lot where previous art-car builds are stored. I asked Sean to walk me through the development and build of *Dragonfly*, an art car that went to Burning Man in 2024 and returned with a few new features in 2025.

BODY TYPE

Entrepreneur Lane Merrifield learned of Sean from the client for whom Sean had built the *Y-Knot Saloon*. “Merrifield didn’t have an exact idea for an art car, but he wanted one,” said Sean. “So he asked: ‘What kind of art car would you want to build if you were going to build something for yourself?’” Sean thought it was an exciting opportunity, since he’d never actually done that.

Sean came up with a concept for this new art car based on a job he once held before he pursued a career as an artist. “I’ve always been fascinated with insects. For many years I was working as an aesthetic entomologist, studying insects — lepidoptera, beetles, butterflies, moths, stick insects — out of a store in New York called Evolution. I was spreading beetles and butterflies, and studying their anatomy. I was just fascinated with them — especially dragonflies.”

The opportunity to use a giant insect as inspiration and to build an art car that is mostly anatomically correct was really exciting. That concept also resonated with Merrifield because he similarly loved insects.

“Once you have the concept (Figure A), then

you can figure out what size vehicle is needed,” he said. When I ask Sean about the different types of base vehicles, I get a tour of the different kinds of art cars that he’s built. “You want something that will work with your design, that you can strip down and integrate into the concepts, and something that’s gonna be reliable, easy to operate, and has good suspension to carry a heavy load.”

A small car that can carry six to eight or so people can be built on a utility vehicle (UTV). A medium-sized car can carry around 20 people and might be based on a light truck body. A large art car like the *Y-Knot Saloon*, a 50-foot long, Western-style saloon that is built to hold 40–80 people, needs something like a bus or semi-truck.

For *Dragonfly*, Sean wanted to put the driver inside its large eyes. In a typical truck, the engine is in front and the driver is set back, which didn’t seem to fit with a dragonfly’s anatomy. He settled on a Daihatsu Hijet (Figure B), a Japanese mini truck where the engine is underneath the deck behind the driver.



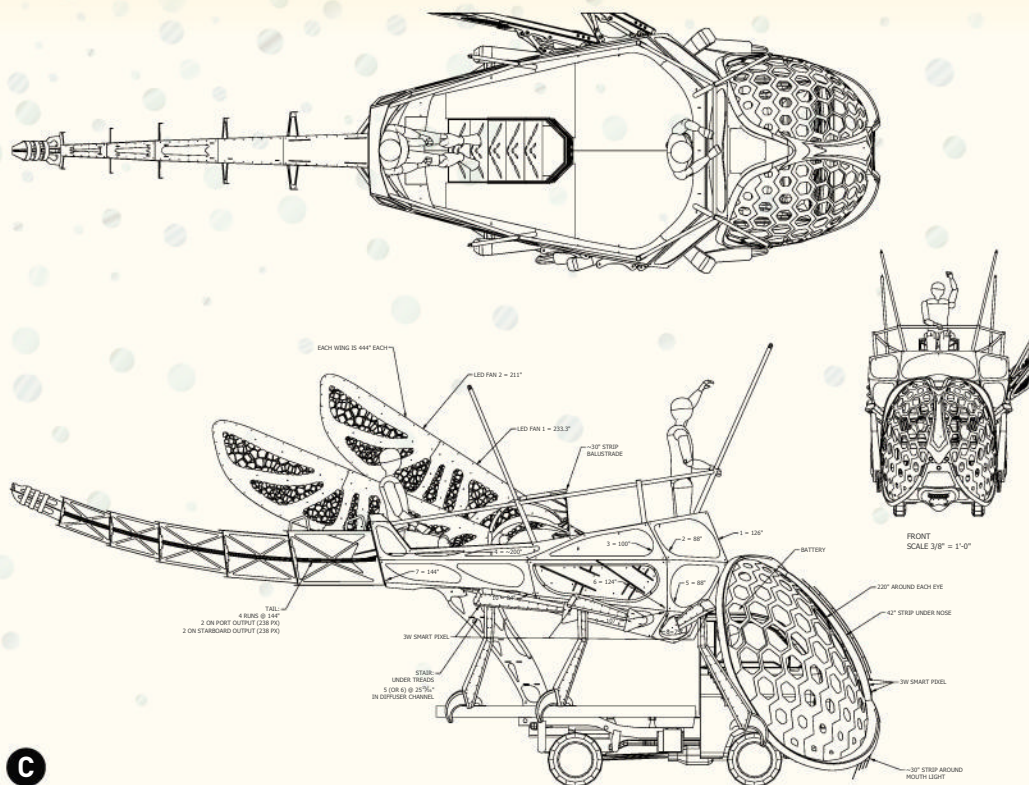
Early rendering of the *Dragonfly*.



The base vehicle was a Daihatsu Hijet kei truck.

Adobe Stock-Bennphoto and Begin Again

FEATURES: Dragonfly Art Car



C

2D design drawings of *Dragonfly*.

Once they found the right vehicle, they began to strip down the bed, cut apart its cab, and build a custom platform. They upgraded the suspension to carry a heavier load, and upgraded the tires. “You don’t want a flat tire on the playa if you can help it.”

FROM SKETCHES TO DESIGN

Sean sees the art-car structure in terms of anatomy, describing the base vehicle as the core or skeleton. Around that, the skin and the systems are built. “We have the shape of the body and how it relates to the tail,” he said. “There’s the thorax and the abdomen. We model these six legs and position them anatomically — a dragonfly has to have legs.”

The entire skeleton (Figure C) was modeled by lead technical designer Tim “Hurricane” Bestman in Autodesk Inventor. Hurricane had to develop custom scripts to define the shape, specifically of the eyes. “Dragonflies have these two massive eyes with the nose in the middle of them,” said Sean. “It was a complex process to model something that was as close to the

dragonfly anatomy as we can get it. We wanted a hexagon as the primary shape, but stretching that across a complex compound surface was a challenge — a perfect sphere would be easier, but this was more of an oval.”

Hurricane’s job was to design 2D shapes that could be cut on a CNC machine, creating flat pieces that fit together to create curved spaces (Figure D).

Sean prefers to work with engineers and designers who are also builders. “If you know how to weld something and you have a fair amount of experience actually working with your hands — knowing what you can do with material and understanding the forces that are placed upon aluminum, steel casts, and iron — that makes you a better designer when you’re working with any of the 3D design programs.”

FROM DESIGN TO FABRICATION

“When we’re building any of our art cars,” said Sean, “we build a kit of parts designed on a computer and process those flat parts using a CNC, water jet, plasma, or laser cutters. But



D The curved sections that will form the *Dragonfly's* eyes.



E Assembly of the *Dragonfly* in progress.



F Upper and lower decks can carry 10 or more people.

sometimes you can't do that. You have to be able to process materials in the shop, whether it's a table saw or a band saw, or a plasma cutter that you're using by hand to drill holes."

Sean said that while the design process took months, the process of putting everything together took only a few days (Figure **E**). "A lot of it was welded, some of it was riveted, and we also used mechanically fastened structural bolts."

And in designing the custom platform, they had to think about center-of-gravity stability. "We decided to go all aluminum to keep the weight down," said Sean.

THE EXOSKELETON

"Insects — especially beetles — have a strong exoskeleton system, and inside that exoskeleton is the heart, 'lungs,' and all the digestive systems," said Sean. "With an art car, we've got an occupiable space for people."

People constitute an unpredictable "live load" that can push the structure far beyond its comfort zone through the dancing and climbing of passengers. "Some art cars that we've built

are for 10–12 people, but they put 20 people on them," said Sean. "Then they're dancing and jumping up and down and pole dancing. We have to predict all of that to try to make sure that what we're building is going to support that."

Dragonfly has lower and upper areas for riders. "The lower-level deck (Figure **F**) is carpeted, and that's where people can sit and engage with the driver," said Sean. On top, there's a platform with a safety railing where 10 people can get up high for an elevated view of their surroundings.

They also built a seat on the tail itself. "It's for the brave people who are willing to climb out on the tail, and there are handholds there for them. They can just sit there like they're riding the dragonfly and flying with it."

LIGHTING AND SOUND

Like any car, art cars need lights, and LED lighting illuminates the pieces and brings them alive at night. "We try to build pieces that look great during the day and then just light up at night with all these amazing programmable, sequenced LED systems that are computer

FEATURES: Dragonfly Art Car



The wings and legs of the *Dragonfly* during fabrication.



The eyes, wings, and legs after they were placed.



Front view of the illuminated *Dragonfly*'s eyes.



Radically illuminated *Dragonfly* at Burning Man.

interesting ways," said Sean. A custom sound system usually features a durable marine-grade head unit, speakers, and amps, which can be controlled via phone or the unit itself.

The custom lighting system is controlled by an onboard computer — often a Mac Mini — that uses software like Chromateq for 3D mapping, sequencing, and programming. The control interface can be an iPad or a simple button box with preset sequences and luminosity knobs. They worked with Mark Janes and John Parts Taylor, as well as JoeJoe Martin on sound and lighting systems.

Adding lighting and sound systems requires an auxiliary power supply. "We don't tap into the main drive battery," said Sean. "If you drain that drive battery, you're dead."

ACTUATED WINGS

The team ran out of time to make the wings kinetic in the first year, so they were just static. "For the second year, we actuated the wings," said Sean. "We redesigned the connection to the

body to make them kinetic."

Sean prototyped and developed a custom support arm system similar to what you might see on a scissor lift. Each wing had a main pivot point, and the scissor-actuation arm supported the 300–400-pound wings and their movement.

Four actuators were installed, along with marine-grade limit switches, to control the outward and inward travel of each wing, ensuring that they operate within safe limits (Figures **G** and **H**).

ON THE PLAYA

The dragonfly art car was disassembled for travel from the Bay Area to Black Rock, Nevada, where it had to be put back together before being inspected by Burning Man's DMV (Department of Mutant Vehicles). The DMV inspectors bring up the art car's application to see how true it is to the initial concept drawing. "They look at how well you mutated your vehicle," explained Sean. "They really want to see that you mutated the base vehicle, that you have transformed it into

MORE FROM ENGINEERED ARTWORKS



Y-KNOT SALOON

Y-Knot Saloon is more than 14 feet wide when fully deployed, but the maximum legal width for commercial vehicles is 8½ feet. So the team designed its floors to fold up and the walls to slide in to make it street legal.



ELEKTRA THE DRAGON

Art cars like *Elektra the Dragon* that incorporate flame effects need to be registered not only with Burning Man's Department of Mutant Vehicles, but also its Fire Art Safety Team.



NAUTILUS

The *Nautilus* submarine weighs 12,000 pounds and was built from a 2005 Eagle TT8 diesel AWD airport tow tractor.



MAGIC CARPETS TWINS

One of the two *Magic Carpets Twins*, designed with programmable LEDs and a surround-sound system for an immersive experience.

Take a deeper dive: engineeredartworks.com/portfolio.

something else."

Sean's client Lane Merrifield was based in Canada, and saw *Dragonfly* for the first time on the playa (Figures 1 and 2). "He was totally blown away," said Sean.

On the last night of Burning Man, it's time to watch the Man burn and everyone just piles on the cars to go watch. "That's a nervous moment for us," said Sean. "We've built so many art cars and they go back every year. I'll see them out there and from a distance, I'll count people: *Look, there's 25 people on that car!*" 🎯

DRAGONFLY ART CAR CREDITS:

- **Lead Artist:** Sean Orlando
- **Executive Producer:** Jay Kravitz
- **Design Engineer:** Hurricane Bestman (XYZ Dimensions)
- **Lighting Design:** Mark Janes, John Parts Taylor, and JoeJoe Martin
- **Fabrication by the Engineered Artworks in-house team:** Sam Andreson, Rocky Boikanyo, Orion Fredericks, Jason Gronlund, and Thom Puhek.

What They Do in the Shadows

Manual Cinema created former President Obama's favorite exhibit at his museum, and may be bringing their dark magic to your town

Written by Kevin Toyama



KEVIN TOYAMA is the books editor at *Make.*, and was formerly the features editor for video game magazine *Next Generation*.

"WHAT THE #%@ \$ WAS THAT?"

I'm standing outside UC Berkeley's Zellerbach Hall, trying to wrap my mind around what I just saw. In the days that follow, I describe Manual Cinema's performance of *The 4th Witch* to people, but it comes out as a word salad: Shadow puppets, and overhead projectors, but with actors and crazy props, and live music, on a giant screen, and ... and ...

"I like to describe it as watching a movie live before your eyes," says Manual Cinema co-artistic director Julia Miller, throwing me a lifeline when we talk a few weeks later. "When you say 'puppetry' — and we are a puppet company — people have pretty specific connotations. They often imagine a talking sock, a *Sesame Street*-type of fuzzy puppet. Even within the Manual Cinema universe we have different ways of describing it, but I would say it's 'cinematic shadow puppetry.'"

A large screen hangs above the stage where the audience watches the show, while below it's all being made in real time. Four overhead projectors — the kind still being used in classrooms across the country — are operated by puppeteers to cast shadows that composite into one master image. Meanwhile, costumed performers are integrating live action with the puppetry, and a music ensemble is scoring what is seen on screen.

Oh, did I mention that *the puppeteers are also the actors*, so they're constantly slipping in and out of costumes and cycling into the camera's view, then ducking out to move their next puppet into place on the projector in a frenetic, synchronized whirlwind?

"It's kind of like choose-your-own-adventure, as far as what you look at on stage," says Miller. "You can watch the final image of the show on the screen above. You can watch the musicians play. You can watch the performers running around to the camera and back to the projector. And you can also try to figure out how we're doing a special effect."

Or, if you're like me, your eyes will constantly bounce around the stage, trying to take it in all at once.



(l-r) Jeffrey Paschal, Myra Su, and Leah Casey operate the projectors while in costume during *The 4th Witch*.



Sarah Fornace and Andrew J. Morgan on the set of *Ten Letters a Day*, one of Manual Cinema's two short films created for the Obama Presidential Center Museum.

Playbill

Manual Cinema is a Chicago-based performance collective, with an emphasis on *collective*. Miller handles the marketing, but is quick to point out that she is just one of five co-artistic directors that include Drew Dir, Sarah Fornace, Ben Kauffman, and Kyle Vegter. In addition to their live performances, they've earned an Emmy for their video work on *The Forger*, a documentary short produced by *The New York Times*; created animation sequences in Jordan Peele's 2021 film remake of *Candyman*; created and performed the visuals on Iron & Wine's 2024 "Light Verse" tour; and most recently, created two animated films for the Obama Presidential Center Museum.

"When I was a kid, I was really into drawing and visual art and thought I was going to go to art school," says Dir. "But then I was asked to paint a scenic backdrop for a high school theater production. And just the experience of being exposed to theater kids, I was like, 'These people are great — they're charming and funny and well-spoken, and the process of putting on a play is cool and exciting.' When you're a visual artist, your work is kind of solitary. But theater

Charlie Doyle, Julia Miller, Adobe Acrobat - yulyulsugeh, Alfa, and Ivaroc

FEATURES: Engineering Emotion

is all about collaboration and depending on one another, and it was so exciting.”

My Kind of Town

Miller was also drawn to the collaboration and camaraderie of theater in middle school and high school, then fully immersed herself in it through Boston University’s conservatory-esque theater arts program. “It was so weird being in the dorms — I remember there were girls going out that were all dressed up and I’ve literally been rolling around on the floor wearing workout-clothes-meets-pajamas as we study really abstract and experimental theater stuff,” shares Miller. “I felt ridiculous to be like, ‘I’m trying to free my natural voice,’ and they’re ... studying chemistry.”

After college, she trained with a theater company in New England, then moved to Chicago to do shows mostly because she didn’t want to be in New York or LA. One was with Redmoon Theater, which created overhead-projector puppetry for *Swan Lake* with the Chicago Symphony Orchestra. Miller was fascinated by its visual, nonverbal storytelling, and she took the puppet designer out for coffee hoping to get her trade secrets. “I asked, ‘What kind of paper do you use? What kind of tape? Tell me everything!’ and she said, ‘You can buy this stuff at Walgreens.’”

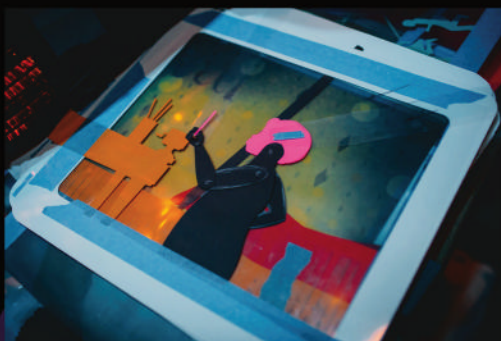
From there, it was fate: Miller’s landlord used to be a medical lecturer and still had an overhead projector in his garage. She asked a Redmoon Theater friend — future Manual Cinema co-artistic director Fornace — if she’d work on a new puppet show with her, but Fornace was already in a show and referred Miller to her partner, Dir. Miller and Dir created *The Ballad of Lula del Rey*, and the two of them performed it with a single projector.

The final principals fell into place when Miller messaged Kauffman and Vegter, a couple of acquaintances whose music she heard on their Facebook account. She asked about using their ambient music for *The Ballad of Lula del Rey*, and they not only agreed, but volunteered to write original music and create the show’s sound design.

“A guy I was dating was a violin maker, and he made us a bespoke shadow screen out of wood



Manual Cinema revised the 20-minute, single-projector *The Ballad of Lula del Rey* into the 70-minute, three-projector *Lula del Rey* that premiered in 2012 and used 200 handmade puppets and 140 sound effects.



Note the transparent lever on this projector puppet from *No Blue Memories: The Life of Gwendolyn Brooks*.

that was collapsible so it could fit in the trunk of my Toyota Corolla,” remembers Miller with a laugh. “That show was maybe 20 minutes long and we performed it at bars and loft spaces and anywhere people asked us to, and everyone helped out.

“And that’s how Manual Cinema was born.”

Exil, Pursued by a Bear

After 15 years, the folks at Manual Cinema have figured out a lot of things, including that being simple and scrappy is part of their ethos. One example of this is a clever effect that can make a character look like it’s moving very fast. In the past, they used a technique of moving a long strip of illustrated transparency across the projector. It works, but its duration and impact are limited by the physical length of the puppeteer’s wingspan,



A six-piece band helped bring *No Blue Memories: The Life of Gwendolyn Brooks* to life.

and how fast it can be moved across the projector.

Instead of thinking of a high-tech version, they simplified it. “We just needed to sell the *idea* of a moving landscape,” explains Dir. “So we cut up some paper to make it look like tree branches, and put it on a stick so it could be spun over the projector lens and look like passing background. It gives just enough of a suggestion of the effect that the audience’s imagination fills in the rest.”

That audience participation — where we aren’t spoon-fed realism and need to actively process visual and audio cues — is part of what makes this art so provocative. I ask Dir about other effects I noticed, and how much fun it is to theorize the mechanics of these visual tricks.

“We want to show you things that you’ve never seen before, moments of spectacle,” says Dir. “Sometimes that means showing you an ordinary object or story point like someone pouring water out of a kettle, but make it happen in an extraordinary way. We’ve found that the more realistic we make it, the less remarkable it feels. That’s where our theatrical background comes in, where you spread a piece of blue silk on stage and actors wave it around, and it represents the ocean. There are these simple acts of imagination that you ask the audience to take part in.”

Innovation and Exposition

More than 500 individual slides or paper puppets are used in a show like *The 4th Witch*, as well

as utensil trays of delicate, tiny puppets that can measure half an inch. But one of the most transformative pieces is something created by Miller.

“I came up with the shadow masks with an eye on functionality,” says Miller. “As a performer I knew what I wanted it to do, and I knew as a maker how to figure it out.” A lot of shadow companies that use live actors will use “hats” with a facial silhouette extending to the side, so performers can cast a profile shadow while facing the screen to watch their movements. But Manual Cinema performers switch directions and move back and forth across the screen, and they need unimpeded vision to see the composite screen because they’re interacting with projections instead of real objects.

Miller’s solution was to create a two-dimensional mask worn only on her profile, so the performer’s profile is on the inside of the mask, and the character’s profile is on the outside of the mask and casts its shadow. It attaches in two places,



Miller invented shadow masks to re-create a character’s profile, made from a few common materials and a whole lot of ingenuity.

FEATURES: Engineering Emotion

at the top of the actor's head and at the mouth, held in place by a custom-fitted mouthpiece made from InstaMorph, a moldable plastic. Filling the silhouette is simple foamcore board with a little piece of upholstery foam that presses against the face to prevent light from leaking through any gaps. "As a performer, the mask helps lock in your specificity of movement because it takes away a big expressive tool — your face — and encourages you to think about your movement in a different way by dropping expressiveness into your body. It's like you're puppeting yourself."

Sharing the Wonder

When Manual Cinema goes on the road for a performance, they often hold workshops led by Fornace. The workshops usually include two parts, the first of which teaches participants how to perform a piece of an existing Manual Cinema show, to learn the technical part of executing a sequence. The second is more sandbox: Fornace gives attendees a bunch of random puppets and slides and an "ingredients list" of things like "a surprise" or "a change of scale," and they create their own story and work as an ensemble to perform it. A kind of self-selection occurs,



Profile masks transform Sarah Fornace (left) and Julia Miller into the main characters in *Hänsel und Gretel*.

where people naturally gravitate toward roles like directing or performing.

"It's very fun to see their sense of wonder unlocked, as they see what we do and then see how they can do it, too," says Miller. And that sharing of skills and tricks is baked into the puppetry community. When Manual Cinema was in its infancy, they had puppeteer mentors who taught them how to work an overhead projector and build different types of shadow puppets. They

While the background is projected behind her, Julia Miller acts in front of the shadow screen to give *Frankenstein* a feeling of an old movie.





Julia Miller and Lizi Breit perform the visuals during Iron & Wine's 2024 "Light Verse" tour.

took those techniques and transformed them into Manual Cinema's style.

"There's a lot of people out there making shadow work and experimental theater who have partnered with us, and hopefully took something from how we do it and brought it into their own work," adds Dir.

Coming Into Focus

While Manual Cinema seems to have mastered their craft, they still find new innovations to push boundaries. Newer productions like *Frankenstein* place performers on the camera side of the compositing screen, so projector shadows are still used to create backgrounds and effects, but a live actor performs in the foreground. The *Frankenstein* story and author Mary Shelley's creation of the book are both part of this production, and Manual Cinema uses different visual language to separate those story lines: Mary Shelley is exclusively in shadow puppetry, while Victor Frankenstein and his monster are in shadow but also on camera in a style that evokes black-and-white silent films.

Similarly, their experience on Iron & Wine's concert tour was a departure from Manual Cinema's tightly woven narratives and more an experiment in capturing how a song feels and creating a visual background for the music to live inside. And their adaptation of *A Christmas Carol* is performed in the style of Victorian toy theater, where people moved miniature figurines.

"At the end of the day, it's not about the tools



Lia Kohl (cello) and Marques Toliver (violin) help tell the story of *The End of TV* through their music.

you're using," says Dir. "It's about how you're using them. We're not the first company to use overhead projectors in this way. Nothing we use on stage is a secret, or a weird piece of technology. It's all stuff that you may have around your house, but we hopefully combine it in a way where it becomes more than the sum of its parts."



Sarah Fornace wears a silhouette mask and holds a transparent red mushroom as "Girl" in *The 4th Witch*.



Who needs Miss Nelson
when Viola Swamp
throws down at The
Planetarium!

Written by Kirk Pearson, Lexi Botkin, and Alex Botkin

S O U I N V E S T M E N T D

How to grow a DIY performance
space from the ground up



KIRK PEARSON, LEXI BOTKIN, AND ALEX BOTKIN
are the co-founders of The Planetarium in Richmond,
California. Join the community at planetariumrichmond.com.

On a Tuesday night in the back of an industrial park — squeezed between a darkened auto-body shop and a quilting surplus store — there is a door that leads to a technicolor, luminescent wonderland. Inside, 16-year-olds in neon wigs are trading stickers with members of a ballet-themed punk band, while a photographer snaps a picture of a professional sword swallower on the couch.

It's your typical Tuesday at The Planetarium.

We opened this all-ages DIY performance venue in Richmond, California, at the start of 2026. Finding us requires a quest through suspiciously beige industrial hallways, but the reward is a disarmingly colorful music venue that feels more like a fever dream than a commercial theater. We book 15 shows a month for performers too “outside the box” for traditional stages.

Here's a secret: anybody can build a theater. And if you play your cards right, you'll end up with a community, too.

We asked our past selves what we wished we'd known 10 months ago when we started this adventure. In the hopes that you, too, can provide this cultural infrastructure for your community, here are our humble recommendations:

1. Write a Mission Statement (Yes, Really)

Every legendary DIY space is held together by a core philosophy. A clear mission statement is your litmus test: When making hard choices about a sketchy booking or a tight budget, ask if it serves the mission.

The Planetarium's Mission: *An all-ages, drug- and alcohol-free community space dedicated to the exhibition and education of experimental performing arts.*

2. Let Needs Dictate the “Hardware”

Consider your user requirements before signing a lease. Warehouses are great for loud bands and late nights, but are expensive to heat and are often isolated. Storefronts have excellent visibility and high “walk-in” traffic, but might be tricky for noise complaints (and your budget). Basements are easy to find, but require strict attention to moisture and egress. Once you know how your



Giant neon signs are great, but it's the music (and opportunity to play said music) that counts, according to Planetarium co-founder Kirk Pearson.



Planetarium co-founders Lexi (left) and Alex Botkin in the business office/marketing department/snack room of The Planetarium.



The Planetarium had a few existing wires that needed to be sorted out before showtime.

FEATURES: Make a Scene

space can be used, it's considerably easier to dream up new ideas on how to use it.

3. Incorporate to Protect Yourself

Running as a "sole proprietorship" (like a lemonade stand) leaves you personally liable if a guest trips on a cable. We use an LLC structure (limited liability company). It's easy to manage for small teams, and if every cent goes back into rent or equipment (deductible expenses), your tax bill remains negligible. You can usually file "Articles of Organization" on your state's Secretary of State website in 15 minutes.

Many people believe a DIY venue needs to be a 501(c)(3) nonprofit — it does not. Being a nonprofit doesn't make you a more ethical business, it just changes how the IRS looks at you (and requires much more paperwork).

4. Be a Good Neighbor

Zoning is how a city dictates who can make noise where. Industrial and commercial zones are your best friends. Regardless of where you land, humanize yourself. If the mechanic next door knows you're a responsible maker, they are much less likely to call in a noise complaint.

5. Safety, Safety, Safety

A DIY venue is only as good as the community that feels safe inside it. Create a code of conduct and post it on the walls. Put it in every booking email. Call people out when they abuse it. If you aren't prepared to kick someone out for being a creep, you aren't ready to open a venue.

If you own the space, expect to spend time filing permits and prepping for inspections, especially with the fire marshal. Often, if you lease or license the space, your landlord is the responsible party — check your agreement!

6. Finding Equipment

While outfitting a venue sounds daunting, the gear itself is pretty straightforward. Below is our baseline startup list with rough retail costs for buying *new*.

Of course, you should first search classifieds and used gear boards — while a solid monitor speaker costs around \$300 new, we got ours for \$50! These full MSRP prices are meant more as a reference point, to inform your budget percentages. This stuff is common, durable, and usually sitting in someone's garage waiting for a second life.



An electric performance/invasion by the mechatronic punk band Captured! by Robots.

Jonathan Botkin (oddbotkin.com), Kevin Toyama

A MIXER!

MIXING BOARD: The mixer (or “board”) should have at least 8 fader channels for your front-of-house (FOH) mix. Crucially, look for a mixer with:

- **At least two Aux channels:** These are independent auxiliary outputs used to send a custom mix to your on-stage monitors.
- **48V phantom power:** Essential for powering condenser microphones or active DI boxes, which bands sometimes have.

Rough cost: \$200–\$400 for a solid, compact 10-to-12-channel analog board.

MAINS AND MONITORS

- **MAIN LEFT/RIGHT SPEAKERS:** Your primary connection to the audience. These two high-wattage speakers can be active (with built-in internal amplifiers) or passive (which require a standalone external amplifier unit to drive them). When starting out, prioritizing active main speakers can save precious real estate and setup time, as you won’t need to mount a separate rack of power amplifiers just to get audio to the crowd.

Rough cost: \$600+ for a pair of entry- to mid-tier 12” or 15” active PA speakers.

- **STAGE “WEDGE” MONITORS (2–3):** These sit on the stage floor, angled up at the performers. They provide a custom mix so the band can actually hear themselves over the room’s natural acoustic chaos. Keep in mind that many classic venue wedges are passive (don’t plug into the wall) and instead rely on heavy-duty, locking Speakon cables for power and signal.
Rough cost: \$150–\$300 per monitor, plus an extra \$200–\$400 for a multi-channel power amplifier if they’re passive.

INPUTS AND CABLES

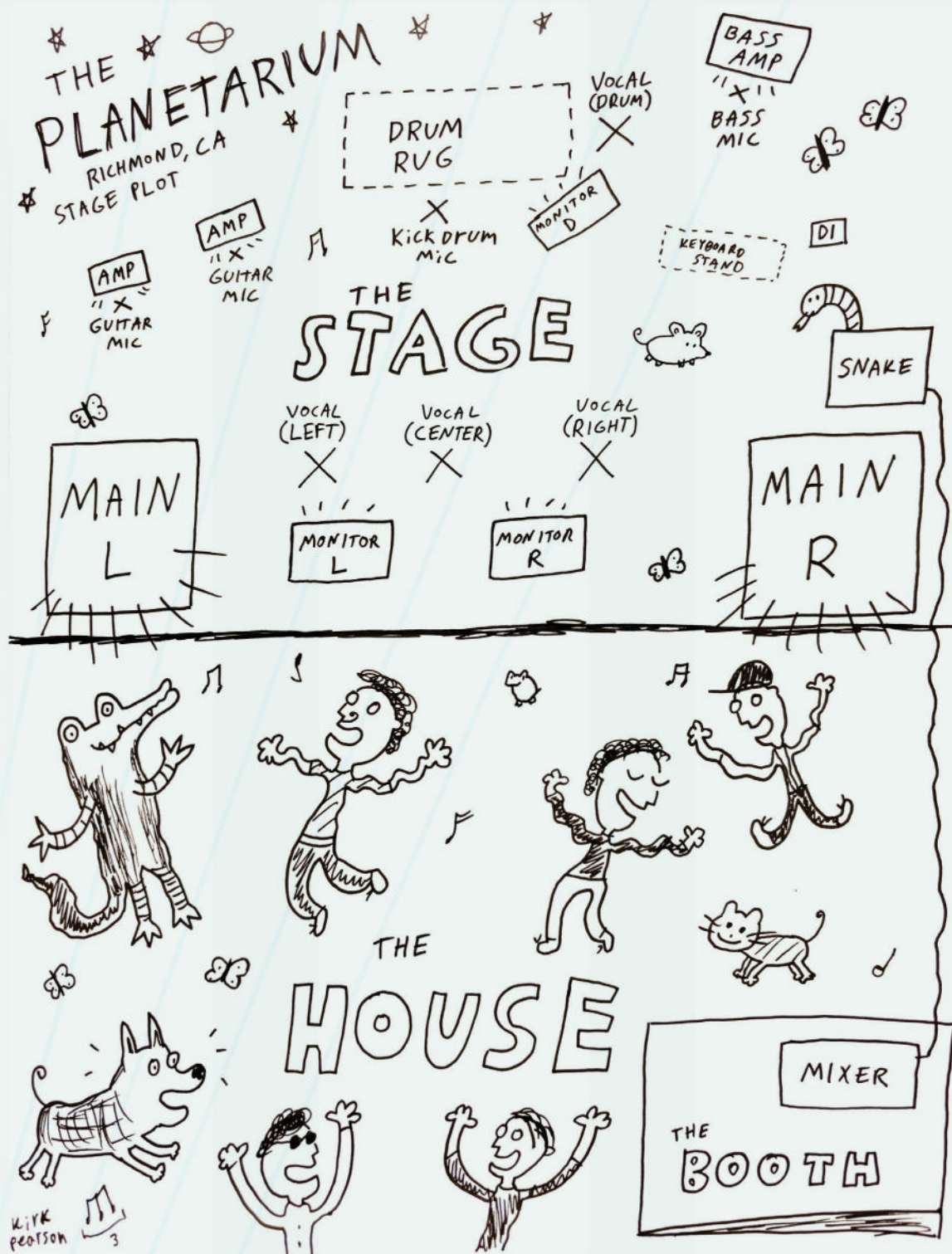
- **MICROPHONES (8–10):** We heartily recommend the Shure SM57 for instruments and guitar cabinets, and the Shure SM58 for vocals. They are virtually indestructible.
Rough Cost: \$90–\$110 per microphone, easily found used for less.
- **MICROPHONE STANDS:** Grab a mix of standard tall boom stands (good for singing) and a few shorty stands (good for kick drums, guitar amplifiers, etc.).



In an age of social media, hyper-local advertising helps get the word out to your community.



Sound artists like Bryan Day may bring (and make!) their own instruments, but they still need to plug into the house system.



Unsure where gear should go? Let this simple setup be your basic guide for what goes where.

Rough cost: \$25–\$50 per stand, easily found used. Avoid the cheap \$15 stands.

- **DIRECT INPUT (DI) BOXES (1–2):** Essential for electronic acts, synth players, or anyone running backing tracks. A DI box safely converts an unbalanced quarter-inch instrument signal into a balanced, low-impedance XLR line that can travel long distances to your mixer without picking up nasty radio hums.
Rough cost: \$30 per box for standard passive DIs, like a Whirlwind IMP 2 or Radial ProDI.
- **CABLES, XLR (15) AND QUARTER-INCH PATCH (5):** You'll need way more long-run XLR cables than you think you do, alongside a healthy stash of quarter-inch patch cables.
Rough cost: \$200–\$300 total for a healthy initial cable cache.
- **AUDIO SNAKE:** If your mixing board is stationed at the back of the room instead of right next to the stage, an 8+ channel audio snake is non-negotiable. Instead of running ten separate microphone cables across a crowded floor where people can trip on them, all your stage XLRs plug into a single heavy-duty stage box, which funnels the audio through one thick, unified cable back to your control station.
Rough cost: \$150–\$250 depending on length (typically 50' or 100').

While this list can sound daunting, chances are you can borrow a lot of this equipment from a local school, church, community center, or elder punk in your neighborhood system ... and they'll probably love to talk your ear off about how it all works.

7. Setting Up a Space

We always recommend setting up your space so that sound runs the *long* way down your room. For most instances, the venue setup on the opposite page works wonders.

8. “DIY” Means “Do It Together”

Running a venue alone leads to burnout. You need a volunteer culture. Create a system where people handle the door, the sound, or the post-show mop-down in exchange for entry. People



If you build it, they will come: Alt-metalcore band No Kings came 400 miles from LA to play The Planetarium.

want to be part of something real, and if you build the infrastructure, they will help maintain it.

9. Practice Financial Transparency

DIY spaces must break even to survive. At The Planetarium, we generally give 60% of the door to the performers. The remaining 40% covers rent and repairs; our staff is entirely volunteers. Always maintain a NOTAFLOF (No One Turned Away For Lack Of Funds) policy. Don't ever let a lack of cash stand between an enthusiastic kid and a life-changing concert!

10. Stay Adaptable

The mission for a DIY space is not always a direct path. The space is just a vehicle for the art. If you outgrow a location for size or safety reasons, carry on! Your core values can transfer to another location. Always prioritize the mission and art first. Nostalgia and rigidity are the death of DIY. Never do something simply because of tradition. Do it because you see the need for it within your community.

Stop waiting for a “real” venue to notice you. Grab a mixer, find a basement, and build the world *you* want to hear. 🎧





Adobe Stock-rogistok

ACTION!

GET READY TO GET OFF YOUR SCREENS, GET OUTSIDE, GET TOGETHER, GET PUMPED, AND GOOOOOO!!

Screens are just simulation. Indoors. Alone. Lame.

Action is what we do for real excitement, out in the real world where real people are. Body moving, blood pumping, wind in your hair. G forces squashing you in the driver's seat or pushing your piloting skills to their max. Hold-my-beer risk-taking. High-fiving in glory or licking your wounds. Adrenaline engaged, all fight-or-flight systems go!

In this issue we celebrate the joys of building thrill machines and dialing them in for maximum fun, and the makers who show us how.

The challenge of inventing new ways to go faster and farther, pressing your face up against

the physical limits of acceleration, gravity, friction, and aerodynamics. And the mysterious arts of tuning motors, propellers, and tires for speed and performance — be it real race cars (page 56), insane electric go-karts (page 34), acrobatic whoop drones (page 44), or jet-assisted ski runs (page 65).

Even the diabolical engineering of toy weapons, in a mostly harmless arms race of foam-flinging extreme Nerf blasters (page 50).

Is there danger? Sure. Is it worth it? Absolutely.

If you love speed, flight, and battle, turn the page for thrilling action projects you can build that go *ZOOM, BANG, WHOOSH!* 🚀

ACTION! FLYWOOD ELECTRIC GO-KART

ZOOM!
ZOOM!

WRITTEN BY SAUL GRIFFITH AND PIERCE O'CONNOR

THE FLYWOOD

BUILD A PLYWOOD ELECTRIC GO-KART THAT
BEATS SUPERCARS OFF THE LINE – AND
TEACHES KIDS ENGINEERING ON THE WAY



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I love making things. I became an engineer because I loved making things, and after a couple of decades of doing it for a living I'm convinced most engineers I meet are in this for the same reason. It's our love language. We can argue about what "making the world better" really means, but we can't argue the fact that engineering is full of lovely challenges and puzzles, and building things that didn't previously exist is fun. Like conjuring, but without the witchcraft.

This article is about making things for fun. And about the new technologies that let us engineer our way out of climate change. But it's also about drag racing.

FOR THE CHILDREN

The technologies of the future are electric. The "electric stack," people call it now. Photons hit semiconductors and become electricity. Wind and rain and geothermal energy are all extracted with generators. Electrons travel through wires and get turned back into light by LEDs and into motion by motor controllers. Energy is stored in batteries. The whole thing is glued together and controlled by microcontrollers. To decarbonize the world is to build out, deploy, and live with this electric stack — the suite of technologies that for the first time in history give us a chance of making this world sustainable.

To understand the electric stack is to understand most of what your kids are going to need to deploy at massive scale to keep this pretty little planet spinning in a better way. But more than that, to understand why this kart will win drag races is to understand how we win at climate action — we make the electric future better, faster, cleaner, leaner, more than anything the fossil record can offer.

Build this go-kart with a kid and you both might just understand that future, and get a little excited about it.

I'm also a big believer in intuition and hands-on education. Engineers can run the math and write the differential equations, but everybody else needs ways to understand the world too — and there should be lots of different ways to get that understanding. My favorite? Hands-on! Full-on! Learn by doing things that make the blood pump



and adrenal glands work overtime.

So this is my electric-go-kart "for the children" project. Yes, it has also been used for plenty of Friday-afternoon hooliganism, a 50th birthday, and a fistful of Saturday-night street races. But underneath the fun is a project that was deliberately, rigorously engineered to be appropriate for a fifth-grader to build and a grandparent to drive. I think of it as a Lego-style assembly that walks you through every part of the electric stack, with an eight-class lesson plan. Turns out if you push that curriculum to its natural limits, you might just break some records.

THE ORIGINAL DESIGN IDEA

Electric skateboards came along about a decade ago and a generation of garage builders quietly figured out something extraordinary: with cheap brushless outrunner motors, an open-source controller from the VESC project, and lithium 18650 cells, you could turn a piece of plywood into an adrenaline machine for under \$1,000. The supply chain — wheels, trucks, motors, ESCs, belts, pulleys, batteries — became cheap and accessible. I wondered why we didn't use the same parts to build a go-kart?

Because, let's face it, e-skateboards aren't for everyone. I'm 50 — my balance is no longer

ACTION! FLYWOOD GO-KART

Olympian. A go-kart, on the other hand, *is* for everyone. From day one I wanted to use the same commodified pieces — McMaster-Carr for fasteners, the e-skate supply chain for everything electronical, one Flipsky VESC per motor, and a chassis I could cut on a laser cutter out of plywood. (The original project folder was called /flywood.)

WAIT, WHAT, WOOD?

Plywood sounds wrong for a chassis until you think about it for 30 seconds. A traditional steel kart frame is stiff on purpose: with no differential, the inside rear wheel has to actually *lift* in a corner so the kart can turn at all. But with one electric motor per wheel and one controller per motor, *the electronics are the differential* — all four wheels can spin at their own speed, and a chassis that flexes a little actually helps because it keeps all four contact patches loaded all the time.

A go-kart at its limit is always traction-limited. The whole engineering game becomes: keep the rubber stuck to the floor and run everything else flat-out.

We had lots of hilarious failures, but this kart now rips. I've added but not tested a handbrake, and it would still benefit from things like torque vectoring — but for the most part this thing is product. Open-source and modular enough that you can take it as a starting point and make it your own, or just build this one and shred some tires. As you'll see here, I've used it for teaching and inspiring kids, and for racing. And I might try to break some records with it in the future.

THE CURRICULUM

The real test of “for the children” came when I taught go-kart building as a sustainable energy on-ramp in Mr. Thomson's fifth-grade class. Mr. Thomson is everything you could ask for in a fifth-grade public-school teacher — memorable and inspirational, and a natural at keeping 60 kids in line. He helped me run an eight-class arc for 60 kids building four karts with six volunteers. I feel like I'm a great engineer, and in Mr. Thomson I felt like I met the teaching equivalent — working with him to inspire kids was almost transcendent. He had preternatural class control, and that balanced my chaos and turned it into



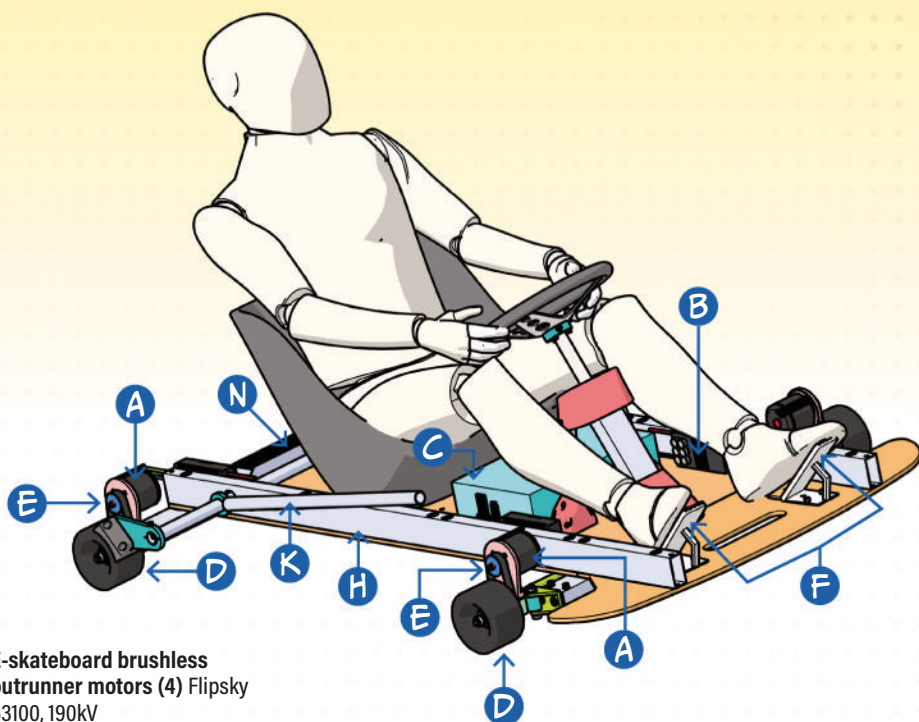
PUBLIC SCHOOL KIDS LEARNING HOW TO DO IT. GO AND BUILD THIS KART WITH 30 PUBLIC SCHOOL KIDS AND CHANGE THEIR LIVES.

unforgettable. We talk of collaborations; this was one of the best I've ever had. He taught me so much about inspiring kids at such a critical juncture, ages 10–12, but also how to keep it calm and make the learning stick.

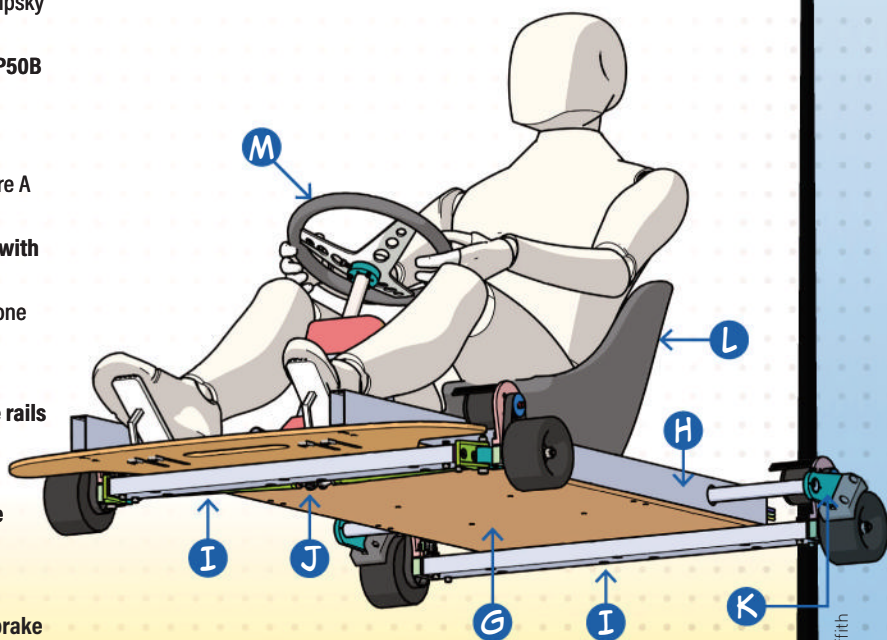
- **CLASS 1:** Build a battery. Copper pennies, zinc-coated nails, Gatorade. We measured voltage with cheap multimeters and lit an LED. The moment with 11-year-olds — “Wait, this is what electricity is?” — is magic. We convinced ourselves that blue Gatorade is the highest voltage, but it is within experimental error.
- **CLASS 2:** Wind motors. With magnet wire we wound the simplest motors. We connected them to batteries, and with cheap tachometers measured the fastest.
- **CLASS 3:** Gears and belt drives. Torque versus speed, which I taught with Lego gears because you know why — they're available and they work.
- **CLASS 4:** Steering linkages. Ackermann steering models in Lego. Watching a kid figure out why the outside wheel turns more than the inside wheel in a corner is its own small magic.
- **CLASS 5:** Chassis cut. Laser cutter, router, plywood, four kart blanks. Aluminum extrusions for stiffness. Some basics — what is an Allen key, what is a locknut, what is stiffness.

THE FLYWOOD 4WD ELECTRIC GO-KART

FASTER THAN A TESLA OFF THE LINE. NECK BRACE NOT INCLUDED.



- A** E-skateboard brushless outrunner motors (4) Flipsky 63100, 190kV
- B** Motor controllers (4) Flipsky FSESC 75200, rated 82V
- C** Battery, 15S3P pack of P50B 21700 cells about 55V
- D** E-skateboard urethane wheels TorqueBoards 110mm×65mm at 74 Shore A hardness
- E** Drive gears, 2.75 ratio, with 15mm drive belt
- F** Pedals (2) one throttle, one rheostatic brake
- G** Plywood chassis floor
- H** Motor rails and **I** axle rails aluminum extrusion
- J** Steering linkages
- K** Mechanical hand brake
- L** Seat
- M** Steering wheel
- N** Rheostatic electronic brake a giant resistor to absorb extra load



ACTION! FLYWOOD GO-KART

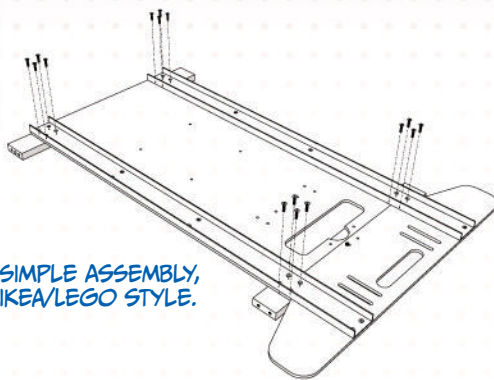
- **CLASS 6:** Painting. My mum is a painter and she came in and taught the kids to mask, prime, and lay down clean coats. It was the most popular class of the eight — remember the need for kids to make it their own.
- **CLASS 7:** Assembly. Six adult volunteers, four karts, every subsystem checked and signed off.
- **CLASS 8:** Race day! Basketball court, top speed electronically capped at a sensible grade-school 10mph, every kid drove the kart they helped build. Smiles everywhere.

THE KID-SAFE VARIANT: SAME KART, SLOWER

For Mr. Thomson's basketball court we built on the same chassis with a deliberately gentle spec: 2WD instead of 4WD, the smallest of motors (5055-class, ~1.5kW each), 95A urethane wheels for wear life. A smaller battery (10S4P). A top speed locked in firmware at 20mph (32km/h).

The whole thing weighs 18kg without the driver, costs under \$1,000 in parts, travels on a roof rack or in the bed of a pickup, and any kid who can ride a bike can drive it. Zero to 20mph still happens fast enough to be fun, and is still traction-limited, especially on harder rubber, because the kart and the kid don't weigh much.

Same chassis, controls, and firmware. Sized down — slowed down. A starting point with which to socialize helmet use and safety protocols. You can of course use larger and more motors and softer wheels, and use the software to keep it safe while your kart still has the capacity to satisfy the bigger kids. That's what we did with one edition, programming the motor controller to switch on command between two modes, one speed limited, one not, so we could swap kids for adults on the fly.



SIMPLE ASSEMBLY, IKEA/LEGO STYLE.

WHEN THE CHILDREN GO TO BED

My favorite movie in the *Fast & Furious* franchise is number three, *The Fast and the Furious: Tokyo Drift*. I love the idea of renting or occupying parking garages after dark and using the deliciously smooth concrete for something more fun than parking the Beamer. One reason to go with skate wheels architecturally is to be able to swap in harder compound tires, either in the rear or all over, intentionally making the car more of a drifter. Traction is great for speed, but lack of traction is great for giggles.

To make a vehicle accelerate fast, or to make it drift well, every subsystem has to be pushed to the limit at the same time. Tires near or over their friction limit. Drivetrain near its tooth-shear and belt-shock limits. Motors near their torque and thermal limits. Controllers near their phase-current limits. Battery near its discharge and sag limits. Wires near their thermal limits. Anything grossly oversized is wasted mass; anything grossly undersized is the part that breaks first.

For my parking garage drifter I never wanted this thing to go faster than 60km/h. I did have one do 100 once and it was terrifying. 60km/h is plenty when your ass is 2 inches off the ground;



it's more important that it gets to 60 quick and handles well. I love being able to switch out soft skateboard wheels for hard, or even soft in front and hard in the rear, to instantly transform it into a real drifting machine.

SO I BUILT AN OPTIMIZER

After six iterations I had a kart that ripped but I knew it was far from optimal, whatever that may mean. The trouble with “push every subsystem to its limit at the same time” is that the subsystems are coupled. Soften the rubber for grip, and the softest achievable compound depends on how many wheels you drive (more wheels means less load per wheel means softer rubber survives). Shorten the gearing for a better launch and you move the motor's thermal operating point — and maybe also fall off the belt's teeth-in-mesh cliff. Add motors and battery mass, and you change the very traction-limited launch you were trying to improve. You cannot tune these one at a time on a Saturday afternoon and trust the answer.

So I did what engineers do when the spreadsheet gets scary: I wrote a model, which honestly is easier than it's ever been if you have some discipline about keeping Claude's sycophancy and hallucinating in check. I built a first-principles, no-curve-fits physics model. A brushless motor built up from turns, can diameter, stack length, and pole count. A battery modeled as an inverter power balance, so the binding limit is pack power (roughly $V^2 \cdot \eta / 4R$), not some optimistic number on the sticker. A tire with actual contact mechanics — a Hertzian patch, load sensitivity, and a thermal limit — so softer rubber genuinely grips harder *and* genuinely overheats and shreds. I built a nine-track lap simulator so the optimization could be geared to track racing if required, not just drag strip speed. I included a brake model (regen, then a rheostatic resistor dump bank, then a crude mechanical brake — no fancy discs) on top.

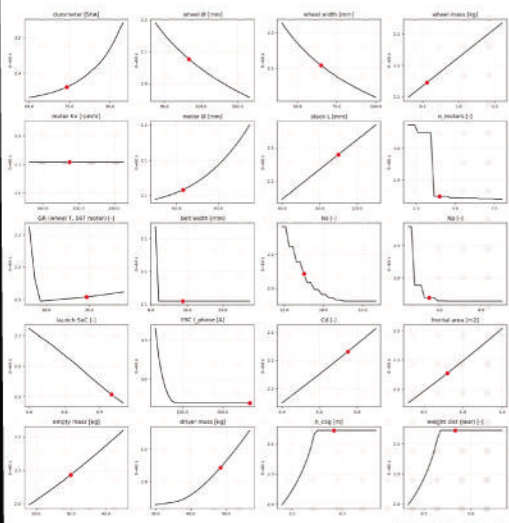
With optimizer in hand I could search for the best kart for cost, for drag time, for racing, and everything in between, and either constrain it to the supply chain — known motors and batteries and belt pulleys — or let it help me custom-design the component that was at the limit, like casting my own wheels. The parameter space is



MR. THOMSON, DRIFTING THE ZWD KART ON RACE DAY.

large: motor choice, gear ratio, belt width, pack architecture, cell resistance, wheel diameter, durometer, wheel count, and downforce.

The interesting question turns out to be what we optimize *for*. My first objective was the obvious one: minimize the 0–100km/h (0–62mph) acceleration time. The optimizer promptly specified triple-parallel battery packs on every single wheel, paying 28 kilograms of cells to buy 13 milliseconds, because nothing in the objective told it that mass costs anything, let alone that there might be budget limits. So human and engineering judgment is still required, only now superpowered by the capacity to search the



A PARAMETER SWEEP OF THE 4WD 0-60KM/H KART THAT SHOWS THE RELATIONSHIP OF EVERY PARAMETER TO SPEED IN THE LARGER OPTIMIZATION. THE OPTIMIZER CAN OPTIMIZE FOR COST, OR ACCELERATION TO 0-60KM/H (OR 0-100KM/H, OR ¼ MILE), OR EVEN AVERAGE LAP SPEED ON NINE SIMULATED TRACKS.

ACTION! FLYWOOD GO-KART

options. The optimizer now knows to minimize time *subject to* the kart staying buildable, drivable, not too expensive, and not on fire. The model is capable of telling you exactly which limit is actually holding you back.

CEILINGS, CLIFFS, AND DIALS

Knowing which limit you're hitting is important, because when it comes to reducing a computer model to a drivable one, you want to know if you're fighting physics or if spending more money will help. There are very different types of limits. I call them **ceilings**, **cliffs**, and **dials**.

CEILINGS ARE DETERMINED BY PHYSICS.

A go-kart at full throttle from rest is traction-limited: it cannot push harder than μ (friction coefficient) times the weight on its tires, full stop. On the stock 4WD kart that's about 1,080 newtons — 65N·m of axle torque — and there is no catalog on Earth with a part that can raise it.

Aerodynamic drag is a ceiling too: power to push air grows with the *cube* of speed, which is exactly why the supercars always walk away above 120km/h (75mph). Motor thermal is a third ceiling: when you hit that limit, magnets delaminate and wiring burns.

You cannot buy your way past a ceiling; you can only change the concept so the ceiling moves — softer rubber, more wheels (to unload each tire), less mass, or, if you're feeling unhinged, suck the whole thing onto the floor with vacuum.

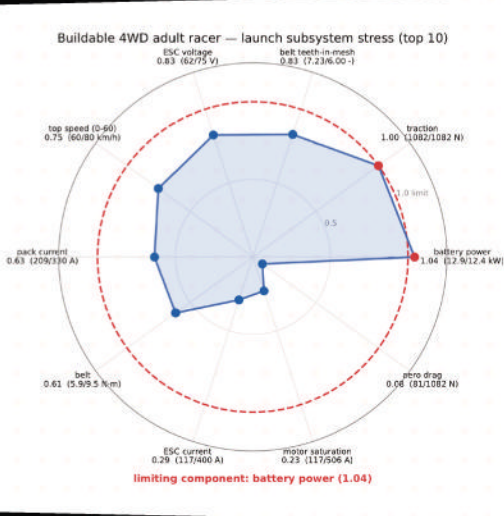
CLIFFS ARE CATALOGS. Most of what you bolt on comes in sizes somebody else chose. Gates Corporation makes HTD-5M belts in 15mm and 25mm widths at intervals of 5 teeth; your buildable widths are 15, 25, 30, 40, 50, and nothing in between. Flipsky's controllers step by current rating — roughly 100, 200, 300, 400 amps — and you can de-rate a 200A controller in software to anything you like, but you cannot type your way to 201.

Cliffs only bite from below, and you clear them in lumps of dollars, weight, and time. The sharpest cliff in the whole machine is the number of teeth engaged on the small belt pulley: below about six, the belt skips and strips. The big-wheeled pneumatic variation I built hit

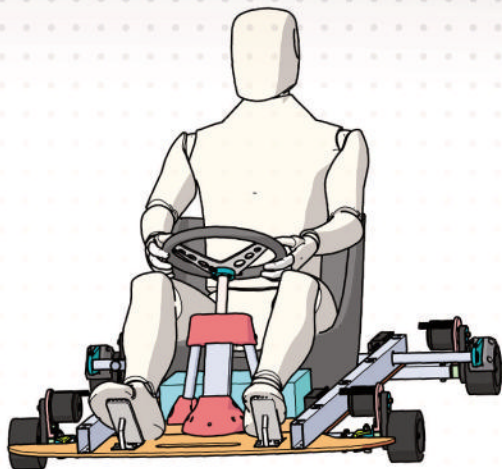
exactly that wall; clearing it forced a lower gear ratio, which re-heated the motor, which forced a heavier motor into the build. One cliff, three coupled consequences.

DIALS ARE WHAT YOU CAN CUSTOMIZE. Seat position, center-of-gravity height, gear ratio (effectively), series cell count — these turn smoothly, and you iterate them until they're right. The boundary between cliff and dial is itself a design choice: buy off-the-shelf wheels and durometer is a cliff; cast your own urethane and it becomes a dial. The moment I let the optimizer cast its own wheels, it dialed in a 70A compound at 120mm×40mm — a size no catalog sells.

A finished design wears its limits on its sleeve. On our 4WD kart, traction reads *1 exactly* — because a ceiling binds at precisely 100%. The belt reads 0.61, because 15mm is the narrowest rung that doesn't bind and the next rung down doesn't exist. That slack isn't waste; it's the shadow of somebody else's catalog. Learning to hear whether you're arguing with μ -m-g or with a product manager in the supply chain is most of what engineering judgment actually is. The solutions are about spending money.



THE BUILDABLE 4WD'S TEN MOST-STRESSED SUBSYSTEMS AT LAUNCH, EACH PLOTTED AS UTILIZATION (DEMAND ÷ CAPACITY); THE RED RING IS THE LIMIT. TRACTION SITS EXACTLY ON IT — THE CEILING — WHILE EVERYTHING ELSE CARRIES HONEST, CATALOG-SHAPED SLACK.



BUILD YOUR FLYWOOD ELECTRIC GO-KART

KART ONE: ADULT RACER 4WD SERIOUSLY QUICK, ACTUALLY BUILDABLE

Start with the 4WD kart that has a real bill of materials and a real price tag. Four Flipsky 63100 motors at 190kV, one FSESC 75200 controller per motor, a practical 15S3P pack of P50B 21700 cells (about 55V), 110mm×65mm TorqueBoards urethane wheels at 74 Shore A, geared 2.75 on a 15mm belt. Off-the-shelf, every part of it, three-stage brake included, for about \$2,761.

It does 0–45km/h (28 mph) in 1.43s and 0–60km/h (37mph) in 2.09s, tops out at 80km/h (50mph), and pulls just under 1g off the line (0.96g in the model). The launch is traction-limited, but it can drive all day. More pack voltage won't really help 0–45 acceleration; this is a 0–60km/h kart, not a 0–60mph one.

This is not a Plaid-killer. But it is seriously quick for \$2,800 of plywood and skate parts: it humiliates every rental kart (~6s to 60km/h), beats most club racers off the line, and over the first stretch to 60km/h hangs with supercars that cost 200 times as much — right up until aerodynamics and gearing let them pull away. Build this kart, take it to a cul-de-sac. Then, when the children are asleep, and you want to see how far you can push it, read on.

KART TWO: UNHINGED 0-60MPH 12WD THE "SUCK YOU, ELON" EDITION

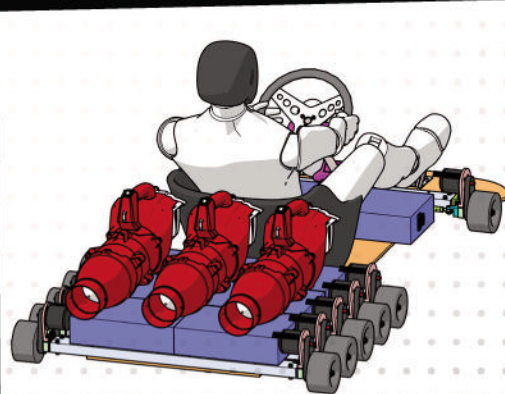
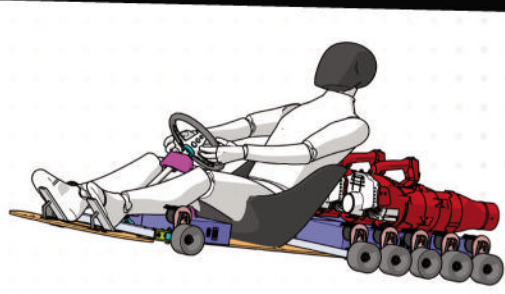
To beat a traction ceiling you have to move it, and the most violent way to move it is adding downforce. Wings and aerodynamics are good,

but don't come into effect until you are moving pretty quick. The world's fastest electric hypercar, the McMurtry Spéirling achieves incredible downforce with twin turbine fans. At this go-kart scale you can do it with garden leaf blowers. Place a rubber skirt like a hovercraft between the plywood deck and the ground and run a few Ego LBX1000 leaf blowers into it. They're cheap and cordless, and won't kill your weight budget.

When told to minimize 0–100km/h (0–60mph) time with a lightweight 50kg driver, the optimizer escalates grip and motors together: 12 driven wheels with 12 custom 8080 motors at 110kV, a 26S12P pack of 312 P50B cells, soft custom 120×40 urethane at 70A, and three Ego blowers generating 2,489 newtons (N) of suction. The model predicts a deranged result:

- 0–60km/h (37mph): 0.66 second
- 0–60mph (97km/h): 1.12s
- 0–100km/h (62mph): 1.18s
- Standing ¼-mile: 14.2s; top speed 107km/h (66mph)

For reference, a Tesla Model S Plaid does 0–60mph in about 1.99s on its own rollout-subtracted number [~2.1s the way the rest of



ACTION! FLYWOOD GO-KART

us measure), and 0–100km/h in roughly 2.1s. A \$1.1-million McMurtry Spéirling does 0–60mph in 1.4s. This plywood-rocket-thing with leaf-blowers beats both of them. Suck you, Elon. It'll top out at 60mph, but remember it was optimized for the canonical American bragging rights number of 0–60. I haven't built it yet, but one of us should. For roughly \$10,000 in build costs we can humble million-dollar cars.

This kart will pull nearly 3g off the line (2.85g for this exact config) — the driver will need a harness and a neck collar, not for crash protection but to stay in the seat!

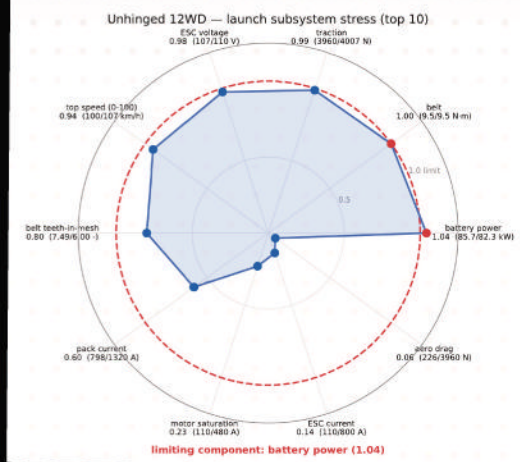
Don't expect it to last, though. With soft 70A rubber that makes the launch possible, the tire-thermal model melts over a sustained lap. This is a drag weapon, not an endurance racer.

KART THREE: INSANE 32WD THE QUARTER-MILE BEAST

The only thing more American than 0–60mph is the quarter mile. We can also steer the optimizer at that: 32 driven wheels, 32 custom 8080 motors at 190kV, a 26S64P pack — 1,664 cells — five Ego blowers for 2,886N of downforce, custom 120×50 urethane at 67A. Peak mechanical power 298kW at 245km/h.

- 0–60km/h (37mph): 0.84s
- 0–60mph (97km/h): 1.35s
- 0–100km/h (62mph): 1.40s
- 0–100mph (161km/h): 2.31s
- Standing ¼-mile: 7.42s at 276.9km/h (172.1mph)

Read that quarter-mile number again, because it's the one that matters. The McMurtry Spéirling runs the quarter in 7.97 seconds. The plywood beast does it in 7.42 — and trips the lights at

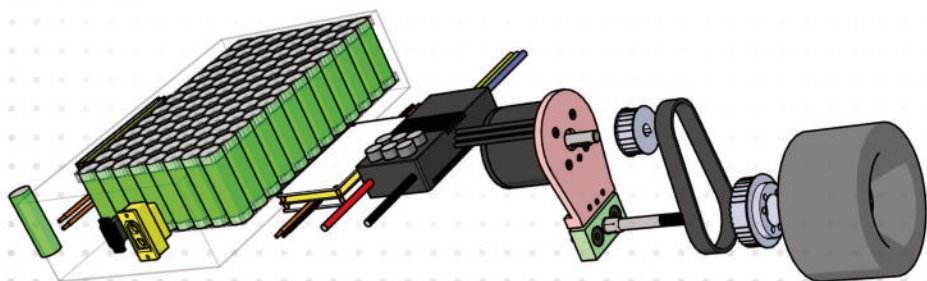


THE UNHINGED 12WD KART'S LAUNCH ROSETTE, WHERE THE 4WD PRESSED ON ONE CEILING, THIS 12WD DESIGN PINS SEVERAL AT ONCE — TRACTION, BATTERY POWER, AND THE DOWNFORCE-FED GRIP THE LEAF BLOWERS BUY — WHICH IS EXACTLY WHAT "PUSH EVERY SUBSYSTEM TO THE LIMIT AT THE SAME TIME" LOOKS LIKE IN A CHART.

172mph. We beat the most accelerative car ever built down a quarter mile, on skate wheels and leaf blowers, for about \$32,000 against its \$1.1 million. We should build this one too, though even I won't drive it; you'll have to find someone more insane, and lighter weight. The only thing that makes this go faster is giving it a lighter driver, and my (ahem) 200lbs are way too many.

FLYWOOD VS. GOODWOOD

The McMurtry Spéirling runs a famous event at the Goodwood Festival of Speed called the Hillclimb — a narrow ribbon of English tarmac they have to prepare especially for it. In 2022 Max Chilton drove the Spéirling up it in 39.08 seconds: an outright record that beat a Le Mans pedigree of internal-





IT'S ON LIKE DIDDY KONG: THE LEFTOVERS AFTER A NIGHT OF RACING FOR SAUL'S 50TH BIRTHDAY.

THE FOUR KARTS PARTS KIT, PERFORMANCE, AND THE POINT OF EACH

	Kids 2WD	Adult 4WD	0-60mph	¼-mile
PARTS KIT				
Driven wheels	2 of 4	4 of 4	12 of 12	32 of 32
Motor	2× Flipsky 7070, 190KV	4× Flipsky 63100, 190KV	12× custom 8080, 110KV	32× custom 8080, 190KV
Controller (ESC)	2× FSESC 75100	4× FSESC 75200	12× FSESC 110300	32× FSESC 110300
Battery	30Q 8S2P (16 cells)	P50B 15S3P (45 cells)	P50B 26S12P (312 cells)	P50B 26S64P (1,664 cells)
Wheels/tires	110×65 PU, 74A	110×65 PU, 74A	Custom 120×40 PU 70A	Custom 120×50 PU 67A
Gearing	2.25 (16/36)	2.75 (16/44)	2.25 (16/36)	1.50 (16/24)
Downforce	gravity	gravity	3× Ego blowers, 2,489N	5× Ego blowers, 2,886N
PERFORMANCE				
Top speed	52km/h (32mph)	80km/h (50mph)	107km/h (66mph)	277km/h (172mph)
0-60km/h (37mph)	n/a	2.09s	0.66s	0.84s
0-60mph (97km/h)	n/a	n/a	1.12s	1.35s
0-100km/h (62mph)	n/a	n/a	1.18s	1.40s
0-100mph (161km/h)	n/a	n/a	n/a	2.31s
¼ mile (ET)	29.62s @ 32mph	19.53s @ 50mph	14.15s @ 66mph	742s @ 172mph
Peak launch g	0.6g	1.0g	2.8g	2.2g
Mass (laden)	68kg	115kg	142kg	324kg
Estimated cost	\$1,630	\$2,761	\$10,077	\$32,044
KEY FEATURE				
	Basketball-court safe	Buildable today; off-the-shelf	Beats Plaid & McMurtry to 100km/h	Beats McMurtry ¼ mile (797s); 172mph

combustion monsters and has stood unbeaten through 2025, on 2,000kg of fan downforce and a million dollars of engineering. We are, by the numbers above, squarely in that car's acceleration tier — to 60mph, to 100km/h, and down a quarter mile — for the price of a used hatchback and a serious trip to the hardware store.

I'm not going to tell you the leaf-blower kart would win the Goodwood; the Hillclimb is corners and bravery and sustained top speed, not just a launch, and our soft drag tires would cook before the first hay bale. But I will tell you that the gap between a million-dollar fan car and a sheet of plywood is now measured in details, not in physics. The electric stack does not care how much you spent. Photons, electrons, copper, and rubber obey precisely the same equations for McMurtry as they do for a fifth-grader with a

laser cutter — and that's what I actually want the kids to feel. The future is buildable. It is cheaper than the incumbents would like you to believe. And it is, unreasonably, more fun.

The thing that would win the Goodwood is good wood shaped like Flywood.

Who's in? It's for the children. 🍷

THANKS ENORMOUSLY TO ARWEN GRIFFITH FOR LOANING ME SOME KIDS FOR THE SAFETY TESTING, TO GEOFF DOLAN FOR INFINITE MOTOR CONTROLLER DEBUGGING PATIENCE, AND TO HANS, BRENTON, AND JAKE FOR MAKING IT FUN.



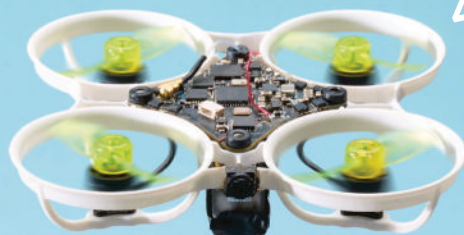
Full BOM, CAD files, VESC configs, the eight-class curriculum, and the complete engineering writeup are at makezine.com/go/flywood.

ACTION! ULTRALIGHT WHOOP DRONE

THE LIGHTEST WHOOOP

BUILD AN ULTRALIGHT
FPV DRONE THAT
WEIGHS LESS THAN
THREE NICKELS!

WRITTEN BY SCOTT A. STEVENSON



BZZZZZ!
ZIP!
ZOOM!



SCOTT STEVENSON builds and flies quadcopter drones in Santa Rosa, California, where as a child he wanted to be a helicopter pilot. During his 20 years in Paris, he started flying R/C helicopters in 2006 and quadcopter drones in 2013, sparking a passion for experimenting and building his own. [youtube.com/WorldScott](https://www.youtube.com/WorldScott)

Build this remarkably lightweight, outdoor-capable, standard-sized 65mm brushless whoop-style drone using off-the-shelf parts, combined with a bit of fine soldering work. If you follow the instructions below, your finished ultralight whoop complete with first-person video camera should weigh between 13.5 to 14 grams — less than three nickels (15g)!

Note that this project requires moderate to advanced soldering skill and steady hands for fine soldering of small components. I recommend you use loupe glasses to magnify your work.

Also, you'll need to know how to configure and troubleshoot Betaflight brushless drones. This is also true for piloting this drone, as it moves very fast!

BUILD YOUR ULTRALIGHT WHOOP DRONE

1. REMOVE MOTOR CONNECTORS

To start this project off, we'll remove the motor connectors on the Matrix flight controller to cut weight. The easiest way is to carefully clamp the controller into a hobby vise so that it sits level in the jaws, with its motor connectors on the bottom. Alternatively you can use helping hands, but take care to attach the clamps where they won't damage any of the SMD components.

Once the controller is in place, add a bit of flux to the solder points of the motor connectors, indicated by the red arrows in Figure A. (Note that the photos here show an older model of flight controller, but the Matrix has essentially the same layout.)

Attach clamping tweezers to a motor connector so they hang beneath, suspended only from the connector (Figure B). Now use your soldering iron to heat the connector's solder joints. I like to cover all three with a small blob of hot solder to help melt them. After a few seconds the weight of the tweezers will make the connector fall out.

Repeat for the other three, then apply flux and use your solder wick to remove excess solder.

2. ATTACH MOTORS

Tin all the motor pads on the underside of the flight controller: apply flux to them again and heat them up one by one, carefully applying solder. During all these soldering steps, always keep your tip clean and free from buildup or debris.

TIME REQUIRED: 2-4 HOURS

DIFFICULTY: INTERMEDIATE-ADVANCED

COST: \$230

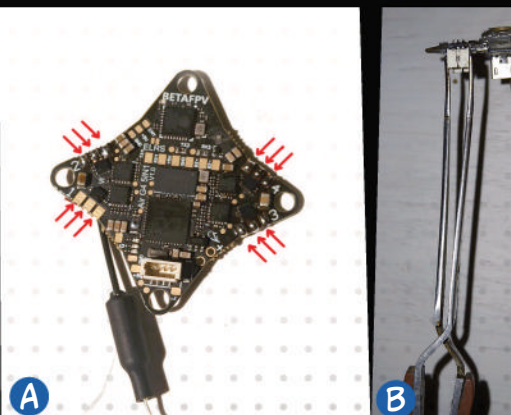
MATERIALS:

LINKS AVAILABLE ON THE PROJECT PAGE AT makezine.com/go/lightest-whoop.

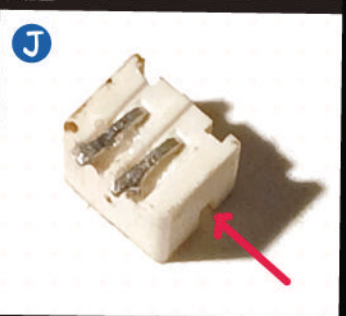
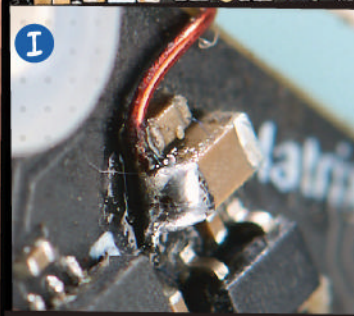
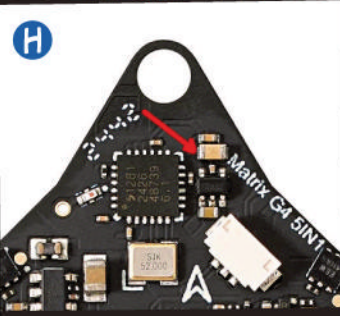
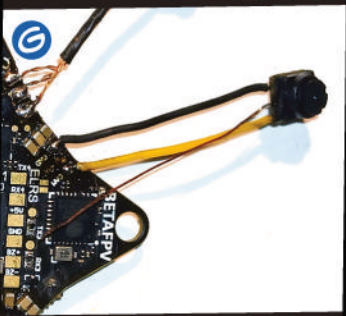
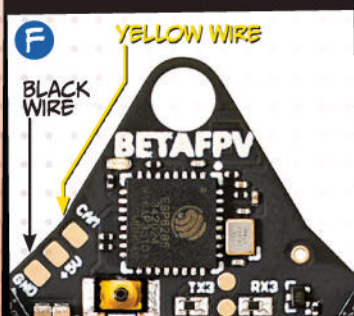
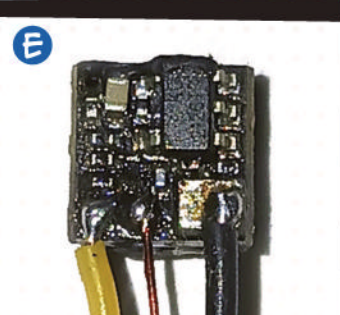
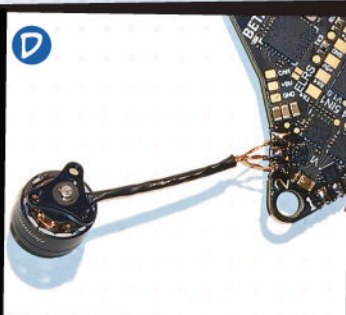
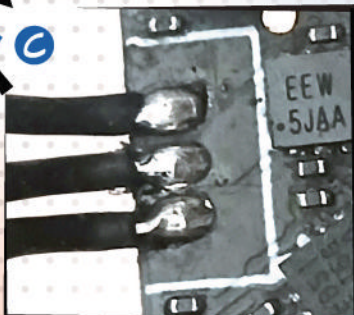
- **Whoop racing airframe** NewBeeDrone Cockroach 65mm Brushless LiteAF
- **Flight controller** BetaFPV Matrix 1S Brushless 5IN1, with mounting grommets. BetaFPV's Air controller is a bit lighter, but less robust for beginners and casual pilots.
- **Ultralight FPV camera** Team Black Sheep Ultra Tiny FPV
- **Brushless motors (4)** Hummingbird 0702 True 30,000kV RaceSpec
- **Motor fixing screws, PEEK plastic, M1.4×3mm (15)** BetaFPV Meteor/Air Series
- **Propellers, 31mm, 4-pack (2 CW, 2 CCW)** Gemfan 1220-4 31mm 4-Blade (1mm shaft), yellow color
- **Battery connector, solid core, JST-PH 2.0**
- **Enameled magnet wire, 32AWG**
- **Silicone wires, 32AWG (2)** 1 yellow, 1 black
- **LiPo battery with PH2.0 connector** Tattu 300mAh HV 1S 75C
- **Video antenna with U.LF connector** Hummingbird RaceSpec 5.8Ghz VTX Antenna U.FL

TOOLS:

- **Soldering iron with fine tip, SMD capable**
- **Fine solder and flux**
- **E6000 glue**
- **Wire snips** to trim wires
- **Nail clippers** to trim propeller blades
- **Clamping tweezers**
- **Hobby vise with rubber jaws and/or helping hands device** to hold flight controller and wires in place
- **Solder wick or solder sucker** to remove any solder bridges or excess solder
- **Calipers for measuring**
- **Hobby knife** e.g. X-Acto blade
- **Small Phillips screwdriver**
- **Electrical tester**
- **Magnifying glasses, loupe style (optional)** recommended



Mark Madeo, Scott Stevenson



Now solder each motor to its pads as shown in Figure **C**, with the spindle of the motor pointing away from you as you solder (Figure **D**).

3. REPLACE CAMERA WIRES

The wires that come attached to the camera are too thick and inflexible. Replace them with 1.3" silicone wires and a length of fine enameled wire, soldered to match Figure **E**. But first the tips of the enameled wire need to be scraped, or tinned with burning hot solder, to remove the enamel.

NOTE: BE CAREFUL WHEN SOLDERING THE BLACK GROUND WIRE ON THE RIGHT TO THE TIMING CRYSTAL ON THE CAMERA CIRCUIT. IF YOU APPLY TOO MUCH HEAT FOR TOO LONG, THE CRYSTAL WILL LIKELY SLIDE OFF, SO BE QUICK AS IT IS A BIT TRICKY TO REPLACE!

4. ATTACH FPV CAMERA

Start by soldering the silicone wires from the camera to the flight controller's camera pads labeled GND and CAM (Figure **F**). As before, flux and tin the pads, then solder the wires in place to match Figure **G**, with the lens of the camera facing you.

The flight controller is designed to power 5V cameras but our ultra-tiny FPV camera needs 3.3V. Fortunately the controller comes equipped with what we need, a 3.3V regulator on board, but it's not broken out as a power source. To access 3.3V, you'll solder your camera's enameled wire to the left side of the SMD capacitor indicated by the red arrow in Figure **H**. Apply a bit of flux at the point indicated, then a small amount of solder to use for the joint. Now solder the camera's enameled wire into place to look like Figure **I**.

5. PREPARE BATTERY CONNECTOR

Remove any wires attached to the PH 2.0 battery connector by unsoldering them, then bend the connector leads flat (Figure **J**). Note the orientation of the notch indicated by the red arrow.

Flux and tin the leads and then solder the red and black battery wires (measure 1.6" in length) to the connector (Figure **K**). Connect a charged battery and use the electrical tester to verify the red wire is positive while the black wire is negative/ground, and fix as necessary. To save a bit of weight you can strip the black wire.

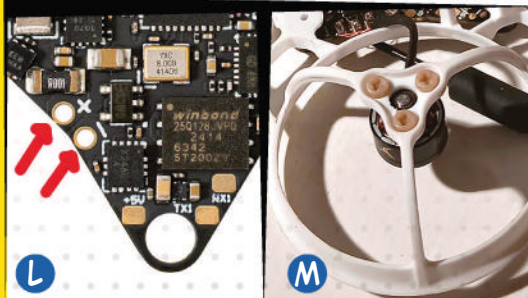
Solder the other ends of the battery wires to the flight controller battery terminals (Figure **L**), red to + and black to -.

6. ASSEMBLE YOUR DRONE

First it's imperative to inspect all your solder joints to verify that all joints are clear, with no bridging. Use loupe magnifiers or the macro zoom on your camera phone. *Any solder bridges can destroy the controller board on power-up!*

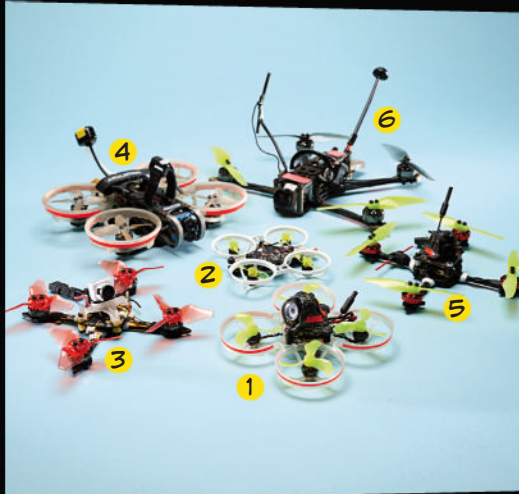
Now place the four rubber grommets into the holes at each corner of the flight controller. Carefully thread each motor through the frame hole for the flight controller and position them into their nacelles. Next, do the same with the battery connector and the camera. Now gently push the flight controller into place, lining up the grommets with their supports, so that it seats fully in the frame.

Secure each motor in its nacelle using three PEEK plastic screws (Figure **M**). Our 15-pack has three spares, and they're fairly robust, but be careful to not overtighten them because their heads can snap off and it's tricky to remove the headless screws from their holes!



KNOW YOUR FPV DRONES

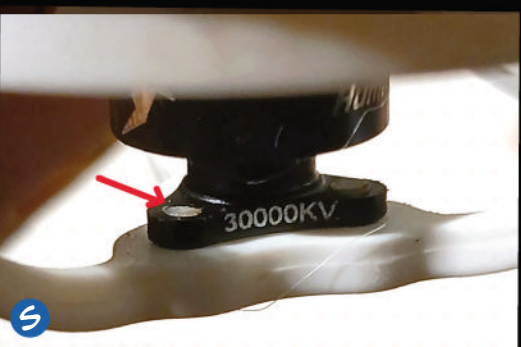
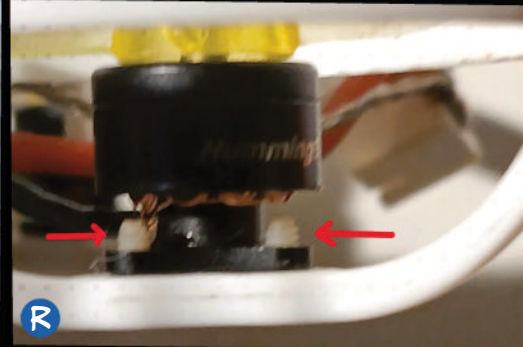
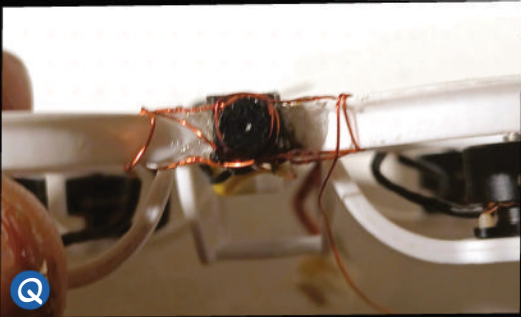
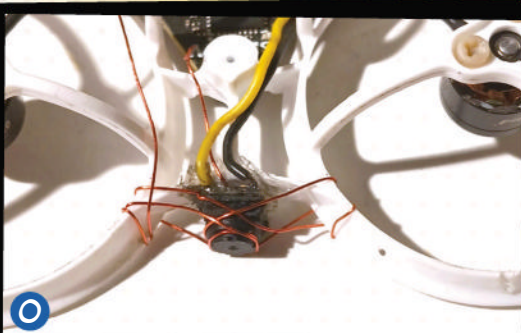
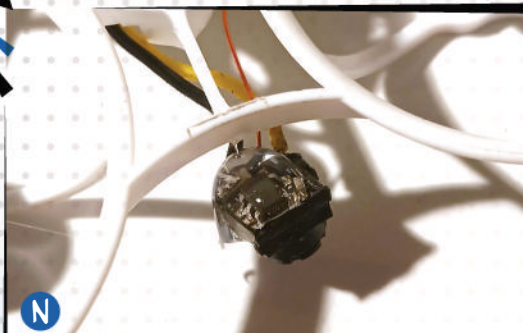
When first-person view (FPV) video drones broke out in the late 2000s, makers quickly adapted them for different purposes. Today they're made for cinematography, for industry, and for war — but these are the ones we make for fun.



- 1 WHOOPS** aka **MICRO WHOOPS** are mini quadcopter drones with ducted prop guards for safety. Fast and popular for FPV piloting and racing, they commonly measure 65mm or 75mm across, with 31mm or 40mm propellers.
- 2 ULTRALIGHT WHOOPS** are the lightest and most nimble, with weight-optimized components and ultra-tiny FPV cameras that trade video quality for acrobatics and pure speed.
- 3 TOOTHPICKS** are similar mini racing drones but open frame, no prop guards.
- 4 CINEWHOOPS** typically sport 3" props and motors strong enough to carry a GoPro-type action camera for excellent video and images.
- 5 FREESTYLE FPV DRONES** are all-rounders: fast and agile for acrobatic flight but still burly enough to carry a quality camera.
- 6 LONG-RANGE FPV DRONES** are built for extended flights up to 20+ miles, with more powerful radios to stay in contact. Ultralight versions are popular too.

—Keith Hammond

ACTION! ULTRALIGHT WHOOP DRONE



7. MOUNT THE CAMERA

Place a dab of E6000 glue on the back of the camera (Figure **N**) and then press it centered onto the frame. Clamp the camera gently in place while the glue sets; here I used a bit of enameled wire to lasso it (Figure **O**). To prevent your image being askew during flight, make sure the camera is aligned from above and from the front (Figures **P** and **Q**).

8. TRIM WEIGHT

Once the glue sets, unclamp the camera and trim any excess glue with your X-Acto blade. You can also reduce a bit of weight by trimming the motor screws as in Figures **R** (before) and **S** (after).

9. MOUNT (OR MAKE) ANTENNA

Attach the Hummingbird antenna to the U.FL connector on the controller.

If you didn't source this antenna, you can prepare one yourself using an antenna wire fitted with a U.FL connector. Starting about 1" from the connector, carefully cut away the black sheath and outer metal ground shielding to reveal the interior antenna wire in its clear plastic covering (Figure **T**). Now cut the interior silver wire to precisely 12.92mm long, starting from the black sheath, using your calipers to measure precisely (Figure **U**).

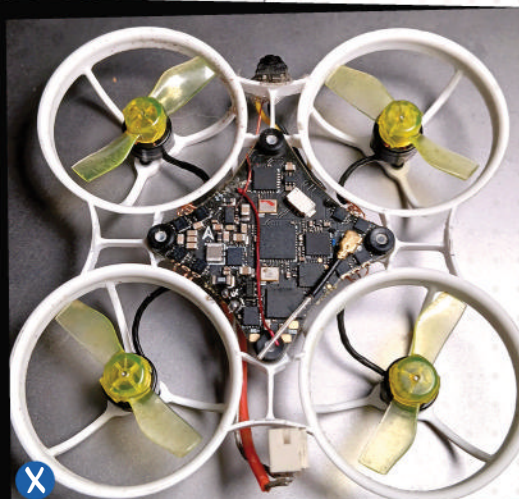
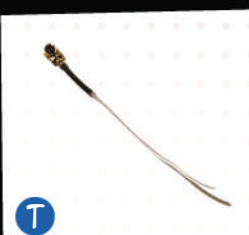
10. MOD AND MOUNT PROPELLERS

Our propellers are a yellow color that fluoresces

well in UV, which is great for locating a lost drone with a UV flashlight after dark. Trim two blades off each, from opposite sides (Figures **V** and **W**). Fingernail clippers easily remove the whole blade leaving no nubs. Place your four trimmed props in their position on the motor shafts. I recommend the “props out” manner as shown in Figure **X**.

WHOOOP THERE IT IS!

All that's left is to connect your ultralight whoop to Betaflight to test out your video feed and configure the drone, particularly its motor directions. I recommend you fly low and slow for your first five flights, in case a build or configuration issue pops up. Have fun piloting and flying your new FPV racing drone! 🚁



YOUR FINISHED ULTRALIGHT WHOOOP AT 13.5 GRAMS, FLANKED BY TWO EARLIER VERSIONS. LET ME KNOW HOW IT GOES, AT DRONE-MAKER@D.R.O!

ACTION! EXTREME NERF BLASTERS

FOAM FLINGERS

NERF MODDING IS A BLAST!
HERE'S HOW TO GET STARTED

WRITTEN BY RYAN CHO



RYAN CHO is a SF Bay Area local with a knack for breaking things and putting them back together. When not getting tagged by darts or working behind the scenes at conventions, music festivals, and LARPs, he can be found tending his garden or being a proud cat parent.

In 1969, a simple toy ball of soft foam called the Nerf ball was introduced and became a massive success, introducing a different way of playing with friends indoors. As time went on the Nerf ball improved, creating alternative basketballs and footballs for kids to enjoy, but our story really starts in 1989 with the first Nerf blaster, known as the Blast-a-Ball, which had one singular purpose: to fling foam.

IF YOU MAKE IT, WE WILL MOD IT

After the Blast-a-Ball was released, the Nerf blaster exploded into multiple different forms, all flinging foam of different shapes and sizes. Like the Nerf ball, the blaster was intended for indoor play with children. However, for many older enthusiasts in the 1990s the question arose: How do we fling foam better? From there, the Nerf modification hobby was born.

As more folks got into playing, they started taking apart their Nerf blasters to figure out how to improve performance. Different blasters had different ways of firing darts, so modders turned to basic engineering and science to boost their blaster's power. Many of the first mods involved removing some parts, adding improvements, or replacing parts with stronger materials sourced via hardware suppliers.

Once they understood the underlying engineering, some modders started to design and create their own blasters from scratch, such as the innovative Rainbowpump by the late **Ryan "McNumbers" Kreterfield**. When Nerf added electric-powered blasters to their lineup, modders added electrical knowledge to their mechanical skills, replacing internal components with beefier batteries, wiring, and motors. For many, this was their introduction into the world of mechanical and electrical engineering, which many younger players would ultimately pursue in their college careers.

A COMMUNITY IS BORN

These modded blasters often exceeded their original intention of being used indoors, so modders would meet up in parks and backyards to test their mods and of course, fling foam. Online communities soon formed around modding and meetups, with **NerfHaven** being

TAG TERMS

You may notice that we use specific terminology used when referring to Nerf blasters. The primary reason is safety: We want to distance ourselves from firearms and weapons, and their legal implications. Similar to how paintball players use "markers," we use Nerf **blasters** to **tag** people with **darts**.

one of the oldest online forums for those looking to get into the hobby and share ideas.

From there, the hobby grew exponentially. Nerf clubs appeared all over the United States and other parts of the world including the U.K., Singapore, and Australia. College students played Humans vs. Zombies, a popular tag-based game where players used blasters to defend themselves from the growing "zombie horde." Nerf influencers and YouTubers — **LordDraconical**, **Coop772**, **WalcomS7**, **Captain Xavier** — became new sources of information for modders everywhere. Modding expanded into other hobbies, as sci-fi Live Action Role-Playing (LARP) games incorporated blasters into their mechanics. Modders created the **Blaster Tag Association** to support competitive leagues across the United States and abroad.

Skilled modders soon started their own small businesses to provide for the growing community; launched by Bay Area local **Luke Goodman**, **Outofdarts.com** is now is a leading purveyor of blaster supplies and beginner-friendly tutorials.



THE LATE RYAN "MCNUMBERS" KRETERFIELD OF MOSTLY HARMLESS ARMS BUILT THE BEST DIY BLASTER OF ITS DAY, THE RAINBOWPUMP, USING PVC PIPE AND OFF-THE-SHELF HARDWARE FROM McMaster-Carr.

ACTION! EXTREME NERF BLASTERS



Left/Right
Up/Down
Zoom

Share & save your Caliburn

Name it!

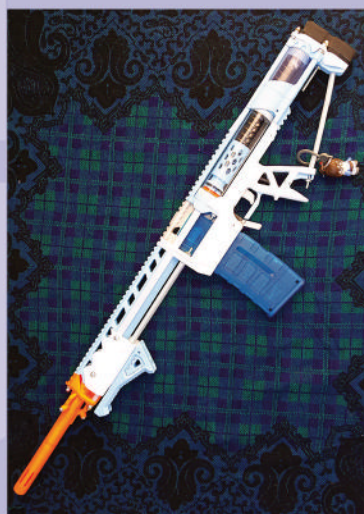
Copy link to build

Bookmark this build

Base	Core Caliburn
Spacer Tubing	White
Rail	Orange
Milan Coupler	Aqua Blue
Plunger	Army Green
Trigger	Army Green
Sear	Blue
Muzzle	Pink
TrenchP	Red
Magwell	ELITE
Elite Upper	White

CAPTAIN SLUG SHARED HIS 3D-PRINTED CALIBURN BLASTER DESIGNS FOR FREE UNDER A CREATIVE COMMONS LICENSE, COMPLETE WITH THIS COOL CONFIGURATOR WEB PAGE.

AT RIGHT: THE AUTHOR'S OWN CALIBURN, NUMBER #189, PURCHASED FROM THE CAPTAIN HIMSELF.



Some, like **FoamBlast** (retired) and **Containment Crew**, worked directly with manufacturers overseas to source and produce custom-made parts and motors, or designed their own PCBs to modernize and streamline the modding process. This did not go unnoticed, as small overseas companies like **Worker** entered the high-performance space to provide their own blasters and kits.

By 2017, Nerf modders had a strong community and a wealth of resources to rely upon. However, it was this year that the incorporation of new consumer tech would add a whole new dynamic to the concept of Nerf modding.

3D PRINTING CHANGES THE GAME

In 2017, NerfHaven user **Captain Slug** (captainslug.com) released designs for the **Caliburn**, an open-source pump-action blaster

that was a combination of 3D-printed parts and hardware (archived at makezine.com/go/caliburn). His generosity and excellent assembly instructions set a new standard for our hobby. He also made hardware kits available for those who printed their own parts, and complete kits for anyone who wanted to assemble the blaster themselves.

The introduction of 3D printing into the Nerf modding hobby was revolutionary. Up until this point, the community relied on modifying existing blasters or building DIY blasters from scratch. With the advent of 3D printing, anyone with CAD skills could create and design their own mods and blasters, and the rest of us could print them out to assemble ourselves. It not only lowered the bar of entry but also added a new facet to the engineering skills already applied by the community.

BUILD-A-BLASTER

So how do you get into the Nerf modding community? These days you can go into a department store and pick up a higher-powered blaster and start playing right away. For starters, check out outofdarts.com/blogs/news/how-to-find-a-nerf-game-near-you and blastertagassociation.com/find-a-league.

Or you can take a look at your favorite blaster and use that as the starting point to modding. Check out the excellent resources at outofdarts.com/pages/getting-started and the forum discussions at reddit.com/r/Nerf.

But if you'd like to build your blaster from the ground up using 3D-printed parts, here are two recommendations:

- **THE SIGNET** designed by Acorn Armaments (Figure A): printables.com/model/1294694
- **THE SLAB (Silly's Lever Action Blaster)** designed by Sillybutts (Figure B): printables.com/model/822836

Both Printables pages have the 3D print files, assembly instructions, and lists of necessary hardware and where to find it. However, these are but two blasters amongst dozens of designs available out there on Printables or Thingiverse, so we invite you to look around and see what catches your eye! 🎯

3D-PRINTED DESIGNS LIKE THE SIGNET (RIGHT) AND SLAB (BELOW) LET YOU BUILD AND MODIFY EVERY PART OF YOUR BLASTER.



STORE-BOUGHT BLASTERS (ABOVE) WILL GET YOU PLAYING RIGHT AWAY, AND SERVE AS YOUR INTRODUCTION TO NERF MODDING WHEN YOU'RE READY TO TACKLE DIY UPGRADES.



YOUR EXTREME NERF ARSENAL

Popular 3D printed blasters like the Caliburn, Talon Claw, and Lynx are just the beginning. Nerf modders are re-creating all kinds of armaments in Nerf form — grenades, mines, cannons, and many more. Check out these incredible extreme builds!

MOAB GATLING BLASTER

Hose those zombies with the Mother of All Blasters, by Thomas Busch of Hamburg, Germany. This six-barrel auto-cannon blasts an insane 50 darts *per second*, with a 500-round backpack magazine (Figure 1). Find the hardware kit on Kickstarter at makezine.com/go/moab, the build guide at gatlingtommy.com/moab-kit, and 3D files and community mods at discord.gg/4a7qnJm4uA.

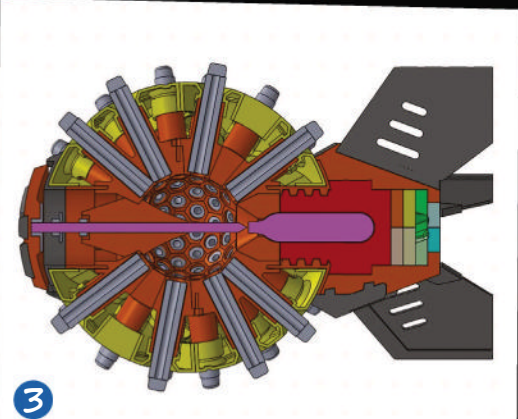
HELLDIVERS 2 AUTO-CANNON

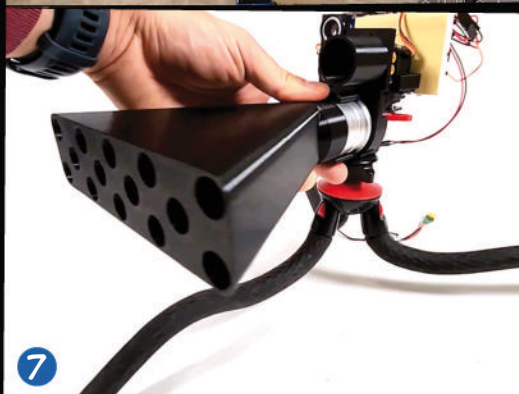
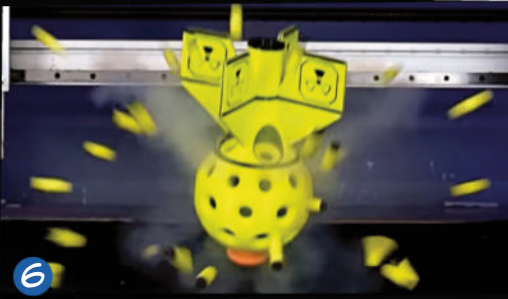
Utah comix creator and Nerf modder Heath Heil, aka Mister Heath Pants, created this massive, manually operated, Mega-dart-firing replica of the AC-8 autocannon from 2024 video game *Helldivers 2* (Figure 2). Watch him cycle it at youtu.be/CDvsuxYRIhQ then download the plans at blasterdownloads.com/product/ac-8-replica.

NERF NUKES

For April Fools Day 2014, ThinkGeek offered a fantastic new product, the 80-dart **Nerf Nuke**! The joke prop was created by Chicago industrial designer Willy Yonkers, who later engineered it to really sort-of work using a **CO₂ gas cartridge** (Figures 3 and 4). Check his build notes at instructables.com/Nerf-Nuke and get the design files for both versions at etsy.com/shop/CubeFire.

Inspired by Yonkers' design, YouTuber Joel Hartlaub (Joel Creates) of Madison, Wisconsin, developed a massive, ground-silo-launched, 100-dart **New Nerf Nuke** powered by **oxy-hydrogen gas ignition** (Figures 5 and 6)! It's an awesome engineering saga (youtu.be/gmmS-bEf-IA) but not the most practical build.





So Hartlaub tried again and hit the sweet spot. His prototype 31-dart **Mini Nerf Nuke** deploys the Nerf armorer's new secret weapon: a rechargeable **40mm air cartridge** in 40MAX or larger 40WAD sizes. Watch at youtu.be/CJHK43uxxtQ, get the 3D files and printing tips at patreon.com/JoelCreatesYouTube, and build at your own risk!

NERF CLAYMORE MINE

California modder Tetsu sells tried-and-true blasters and kits (foamtechnician.com) but he also shares his wild Nerf experiments on YouTube, including this 28-dart Claymore mine, motion-triggered by PIR and ultrasonic sensors, and powered by 40MAX/40WAD air cartridges (Figures 7 and 8). Watch him develop and test it at youtu.be/3XPTJRM_CXs and remember, Front Toward Enemy!

—Keith Hammond



THESE 40MM AIR CARTRIDGES, DEVELOPED BY CHINESE AIRSOFT PLAYERS, ARE MAKING NEW NERF ARMAMENTS POSSIBLE.

ACTION! RECORDING TIRE PYROMETER

RACE CAR TIRE PYROMETER

LOG YOUR TIRE TEMPERATURES AND
TUNE YOUR RIDE FOR FASTER TIMES

WRITTEN BY BRIAN SMITH



BRIAN SMITH has raced karts and cars for over 40 years. While dreaming of F1, he's had a long career in software and hardware development, and has put it to use in the interest of going faster!

Brian BMW Z4 12:46pm 10/20/2024

RR	O	C	I
98.6	96.9		

VRROOM!
VRROOM!

C	RF	O
113.2	109.4	108.4

LFO	C	I
104.7	104.1	

Yamura Motors LLC Recording Pyrometer



Since skipping my college graduation to buy a racing kart, I've raced a variety of cars over the years — sprint and enduro karts, Formula V and Formula Ford, and now SCCA Solo (autocross) with a Toyota MR2 and a BMW Z4. All very different cars with one thing in common — tires.

Ultimately, tires determine how much grip is available for the driver to use for acceleration, braking, and cornering, so knowing their condition is an important data point for optimizing car and driver performance. In this project I'll show how to measure and log your tire temperatures with a DIY recording tire pyrometer based on a cheap ESP32 microcontroller.

If racing's not your passion, you can use this project as a basis for all kinds of compact, portable data recorders by changing the attached sensors. Want to get soil moisture measurements from your garden? GPS positions? Sound volume? Light brightness? Air quality? Any sensor that has an I²C or SPI interface and an Arduino library is easy to add to this basic design.

TIME REQUIRED: A WEEKEND

DIFFICULTY: INTERMEDIATE

COST: \$75-\$120

MATERIALS:

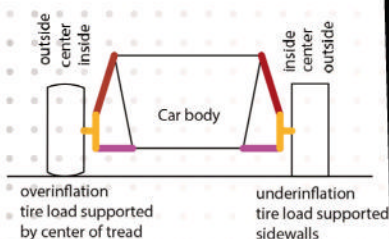
- ESP32 DevKitC microcontroller dev board such as Amazon B09KLQF4RR. You can also use Arduino ESP32 boards.
- LCD touch screen display, 4", 480×320 TFT Amazon B0CKRJ81B5
- Thermocouple amplifier board, I²C, MCP9601 Amazon B09GZMPNST, Adafruit 5165
- Real-time clock module, I²C, DS3231SN B0CPF8X8NW
- K-type thermocouple racing tire temperature probe, 0°C-200°C B07H5H1YV9, PerfectPrime TL3000
- Breadboard-style PCB, double column B07YSCGBL7, ElectroCookie ECPB_DH_B_3P
- Switches, momentary pushbutton, 12mm (3) B0C3GQZQHH
- Switch, latching pushbutton, 12mm, with LED B09BKWB95G
- SD memory card, 1GB B07RP74DNW
- Battery terminals, AA: single (2) and dual (3) B09NBQLDSG
- K-type thermocouple connector mini plug B09WLRW5B
- Schottky diode, 1N5817, 1A 20V B07Q5HISLY
- K-type thermocouple wire, 6" (optional) B0768JJT4R, for better connection to thermocouple amplifier
- Brass threaded inserts for plastic, 2-56 thread (15) McMaster-Carr 97171A110
- Socket head screws, 18-8 stainless steel, 2-56 thread (15) McMaster-Carr 92196A077
- Solderless breadboards, quarter size (3) B0D9L93DL9, for testing
- PETG 3D printer filament (if printing your own enclosure)
- Header pins, 2.54mm male and female
- Hookup wire
- Screws, 18-8 stainless 3/8" long, 2-56 thread I also use #2 stainless washers.
- Double-sided tape
- Batteries, AA (4)
- Coin cell, CR2032

TOOLS:

- Soldering iron and solder
- Wire cutters/strippers
- Multimeter
- Screwdrivers
- Scissors
- 3D printer (optional) if printing enclosure
- Computer with Arduino IDE free at arduino.cc/download. You could also use Visual Studio Code.
- USB cable compatible with your ESP32 module

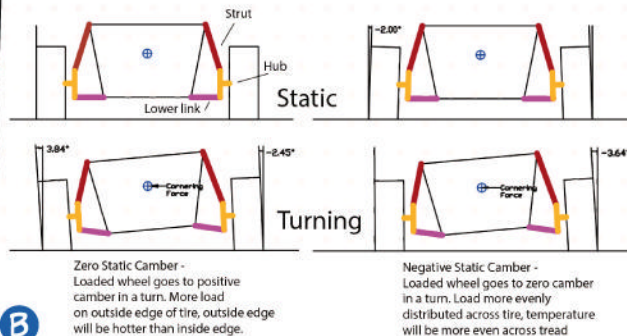
ACTION! RECORDING TIRE PYROMETER

TEMPERATURE MEASUREMENT LOCATIONS



A

CORNERING LOAD TRANSFER AND SUSPENSION MOVEMENT



B

WHAT TIRE TEMPERATURES TELL YOU

When talking about tire temperatures, racers refer to the inside, outside, and center of the tread (Figure A). The grip available from a tire depends on how much of the tire is in contact with the ground, and the vertical force or load applied to the tire. Ideally, you want to set up the tires and suspension so the load across the tread is as even as possible, generating the most grip (Figure B).

If the air pressure is too high, the contact patch shrinks as the tread crowns at the center of the tire. Too low, and the inside and outside edges of the tire do more of the work because the sidewalls are supporting more of the load. As tires heat up, so does the air inside them, so you may need to start a session with lower than ideal temperatures. Measuring temperatures and air pressures at the end of the session helps you find the right air pressure for each tire at the start.

Tires generate grip from friction, and friction generates heat. So measuring the temperature of each tire at inside, center, and outside points tells you how hard each part of the tire is working to generate grip. Ideally the temperature across the tread should be consistent, and in the best working range of the tire. If it's above or below optimal, you get less grip. Too cool? Maybe switch to a softer tire for more grip at lower temperatures. Too hot? A harder compound tire gives more grip at higher temperatures.

It's possible to take tire temperatures even while the car is in motion using non-contact IR thermometers. But tire pyrometers have a tire-specific temperature probe that pushes into the

tread to get a more accurate temperature. With a few easily available parts and some soldering skills, you can build a recording tire pyrometer that has more features than commercially available pyrometers costing several times more.

RECORDING TIRE PYROMETER DESIGN

The RTP's functions define the hardware needed:

- **Read and display tire temperatures:** K-type tire pyrometer probe and K-type thermocouple amplifier; TFT display for visibility outdoors
- **Record temperatures:** microSD card
- **Access the web for setup and to display results on phones/tablets:** ESP32 microprocessor
- **Timestamp results:** real-time clock (RTC)
- **Handheld unit:** 3D-printed enclosure suitable for outdoor use
- **Support multiple car/driver/wheel configurations:** simple, fast user interface

1. ENCLOSURE DESIGN

The hardest part of this project was the enclosure design! You need to use one hand for the tire probe, so the enclosure should fit comfortably in your other hand. It's used outdoors, so it needs to be at least water and dust resistant. The screen needs to be visible, the batteries accessible, the buttons usable with one hand, and the temperature probe cable needs to be out of the way. Figure C shows how I laid out the PCB for the components to fit inside the box, using the electronics design tools in Autodesk Fusion. You can learn more about how that works in the extended version of this article at makezine.com/go/race-tire-pyrometer.

2. PRINT THE ENCLOSURE

Generate STL files from your own enclosure design, or download my STL files from github.com/bbsmith24/YamuraPyrometer. There are four pieces to print: the box; the box cover that holds the display, buttons, and control board; and the battery box and its cover. I use PETG for better temperature stability. Don't leave a PLA box sitting on your dashboard on a sunny day!

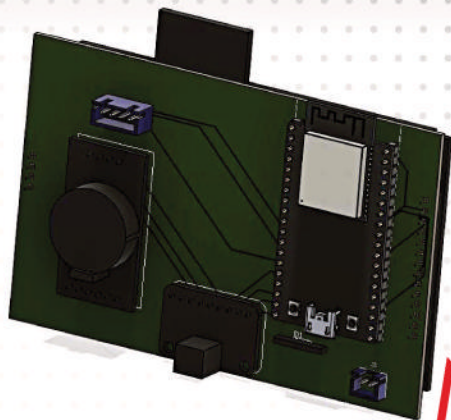
The box parts are screwed together. I use heat-set brass threaded inserts (Figure D), especially for screws that will be removed frequently like the battery box cover. These are easy to add to a 3D-printed part—just push the insert into the hole as far as it will go, then push it the rest of the way with a hot soldering iron (Figure E). These inserts hold in place well, and will survive many disassemble/reassemble cycles. Also press the battery terminals into the battery box as shown.

Solder the polarity protection diode to the positive terminal of the box and add wires to connect the batteries to the control board.

Install the pushbuttons in the box cover, leaving enough wire to connect to the control board. Push the thermocouple socket into its hole in the walls.

3. ELECTRONICS

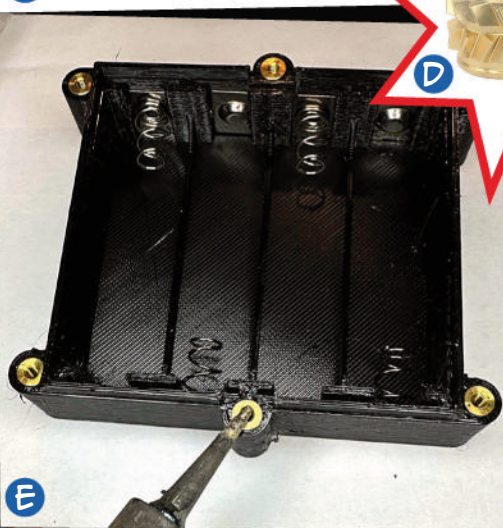
Follow the wiring diagram (Figure F) and lay out your components. There are a lot of connections, so I like to use consistent color wires to make



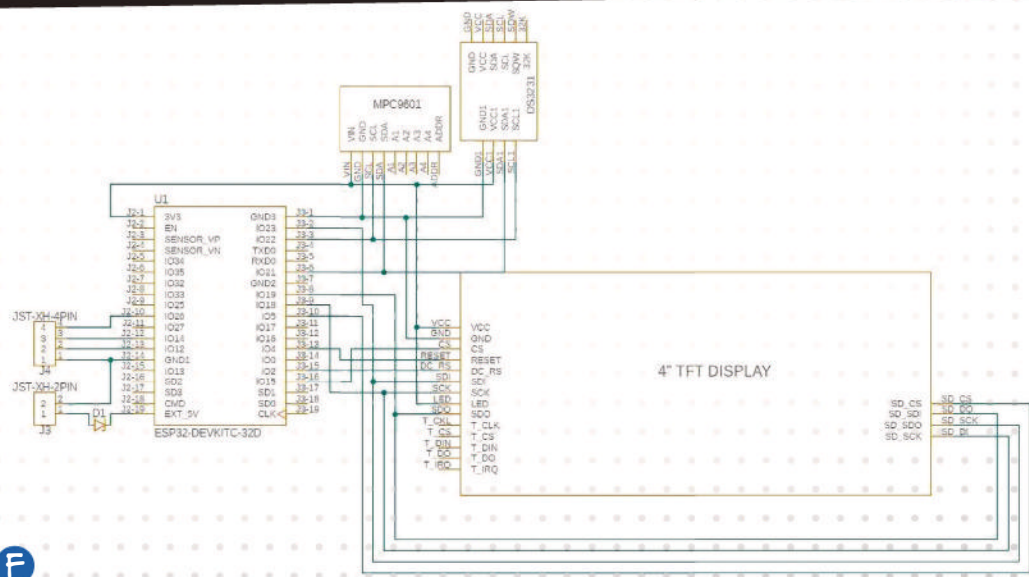
C



D



E



F

ACTION! RECORDING TIRE PYROMETER

checking the connections easier. You can test the whole circuit on three small breadboards (Figure G) before soldering the PCB.

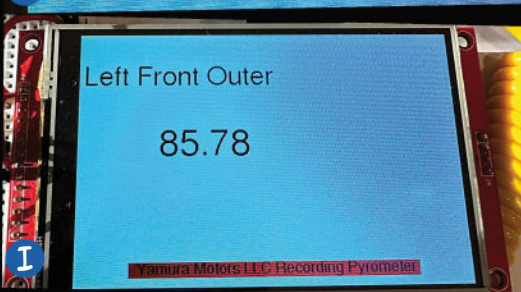
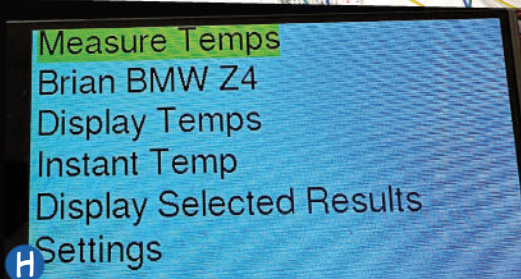
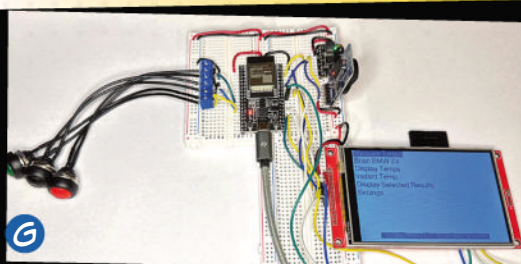
- **POWER:** **Red** (+) 3.3V logic; **Black** (-) to control board battery in and ground; and **Orange** (+) 5.0V battery voltage. I don't want to accidentally supply 5V to the 3.3V chips, so I use a different color.
- **I²C BUS:** Data to/from RTC clock module and thermocouple amplifier. **Blue** SDA, **Yellow** SCL.
- **TFT SPI BUS:** Control TFT display, send data to/from SD card. **Blue** Controller SDO to Peripheral SDI; **White** Peripheral SDO to Controller SDI; **Yellow** SCK; **Green** chip select for TFT screen.
- **TFT DISPLAY:** **Red** 3.3V supply to TFT screen and SD card slot; **Yellow** DC_RS; **White** RST (reset)
- **SD CARD SPI:** **Blue** Controller SDO to Peripheral SDI; **White** Peripheral SDO to Controller SDI; **Yellow** SCK; **Green** chip select for SD card.

Check each bus for correct wiring as you go, using a multimeter set to continuity. Also check that there are no connections between either 5V or 3.3V and ground, and no unintended connections between adjacent pins. A little extra time now will save you headaches trying to find a shorted-out button or nonfunctional TFT display later. Shorts between 5V or 3.3V and ground are usually easier to find but more catastrophic — something will get hot and burn out.

4. PREPARE MICROSD CARD, FLASH FIRMWARE TO ESP32

Download the firmware (*YamuraPyrometer.ino*) and initialization file (*YamuraPyrometer.h*) for the microSD card from my GitHub repo. These files contain the default settings and configuration for the RTP. Copy the files to the microSD and insert it in the slot on the back of the display board.

Start the Arduino IDE. Make sure all the required libraries (listed in *YamuraPyrometer.h*) and board definitions are installed. Connect the ESP32 board to your computer, select the board and port, then build and flash the firmware to the ESP32. If all your connections are correct,



you'll see status messages on the screen, then the main menu (Figure H). Check that the menu up, down, and select buttons work. For troubleshooting tips, check the extended article at makezine.com/go/race-tire-pyrometer.

TAKE TIRE TEMPS! USING YOUR RTP

Use the up and down buttons to change the highlighted action. Use the select button to choose the highlighted action:

- **Measure Tire Temps:** The display shows the current tire and measurement position; **** indicates measurement hasn't started. Push the tip of the probe into the tire tread and press the select button to start measuring. Temperature is displayed while it stabilizes (Figure I). After it stabilizes, repeat for the next tire/position.

At the end of the measurement cycle, all temperatures are displayed in a grid. Highest temperature for each tire is highlighted in

red, lowest in blue (Figure J). Press select to return to main menu.

- **Select Car/Driver:** Choose the driver/car for the next measurement.
- **Display Temps:** Most recent results, in a grid.
- **Instant Temp:** Useful for measuring current ambient temperature or track temperature.
- **Settings:** Set various device parameters

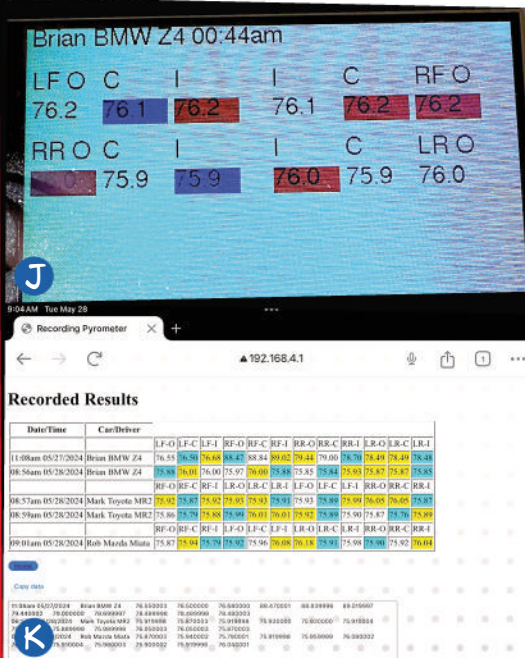
USING THE WI-FI INTERFACE

Connect to the **YamuraPyrometer** Wi-Fi network from a phone, tablet, or computer. Open a browser and enter the IP address of the RTP (shown in the setup page). The first time, you'll need to use <password> to connect.

Now you can review recorded temperatures (Figure K) and car/driver settings, or change the settings of the RTP.

AT THE TRACK — APPLYING WHAT YOU'VE LEARNED

You've just completed your run through the cones. You've measured your tire temps, now you have just enough time to adjust your suspension and tire pressure before the next run! Learn how at makezine.com/go/race-tire-pyrometer — then start your engines. Go! 🏁



MORE RACE DATA PROJECTS

Serious racers use data to go faster. I've made a few spinoffs of the recording tire pyrometer. You can build these too:

RACE DATA LOGGER

Often there's no time between runs to pull out the microSD card for reading on another device. This project uses an ESP32 running Adafruit Airlift so I can log and read speed and position (GPS), acceleration (IMU), steering, and throttle data remotely on a tablet or laptop. makezine.com/go/race-data-logger



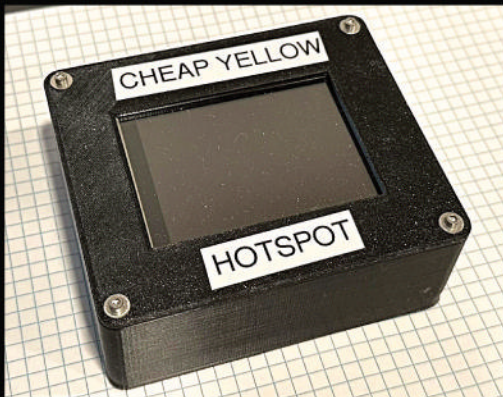
MULTI-TURN STRING ROTATION/ DISPLACEMENT SENSORS

I needed a couple of string potentiometers to measure steering angle and throttle position, but the prices gave me major sticker shock! So I made my own for around \$20 using a donor retractable spring and a magnetic rotation sensor. makezine.com/go/string-potentiometers



CHEAP YELLOW HOTSPOT

At the track, there's generally no Wi-Fi available. To quickly transfer data between the logger and viewer, I use FTP to send the file wirelessly. For cheap, battery-powered Wi-Fi, I use this ESP32-based Cheap Yellow Display that boots in station mode and provides a hotspot. makezine.com/go/cheap-yellow-hotspot



ACTION! MAKE IT AND RACE IT

IF YOU AIN'T FIRST, YOU'RE LAST

YOU DON'T HAVE TO BE RICKY BOBBY
TO RACE IN THESE CRAZY LEAGUES

WRITTEN BY KEITH HAMMOND



VROOM!
VROOM!



1

1 POWER RACING SERIES

A favorite spectacle at Maker Faires from Orlando to the Bay Area, this league takes store-bought kiddie Power Wheels cars and hot-rod's them with beefy kart motors and frames to compete in races all over the U.S. (see "Hack the Track," *Make*: Volume 33). The comedy of grown-up drivers crammed into overclocked tike buggies and whipping through the straw bales never gets old, and you can expect a hilarious announcer calling the race, too. I always like to visit pit row where teams frantically repair their cars for the next run, and opponents lend a helping hand.

For beginners, the barrier to entry is low. There's a \$500 per vehicle spending limit to keep things competitive, and they've even got grants for new teams and travel. Get started at powerracingseries.org.

2 24 HOURS OF LEMONS

Ready for real road racing? Buy a crap car for under \$500 and enter this junker endurance race series, on dedicated road courses across the U.S. Rookie teams are accepted automatically! You'll enjoy big scoring handicaps for the hooptiest rides (advanced age, wretched country of origin,



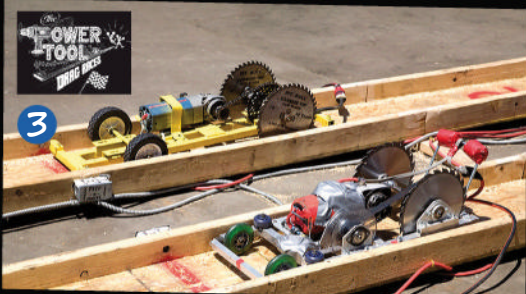
24 HOURS OF LEMONS

racing for real people

2



WE'RE
NUMBER 33!
"MAKE: WAY"
RACING TEAM
PROUDLY
PLACES IN
THE TOP 40
IN "24 HOURS
OF LEMONS"
ENDURANCE
RACE, 2008.



3



4



RACE TRACK

MINI 4WD CARS

MOTOR UPGRADES

general awfulness) and a massive bonus for goofy themes or costumes. In 2008, our own Make: Way racing team proudly placed in the top 40 in the Seaside, California, event (see "We're Number 33!" in *Make: Volume 16*, makezine.com/article/maker-news/were-number-33).

Not quite ready to drive? Come as a race spectator, or check out a Lemons rally or car show. Learn all about the league and the rules for drivers and their (miserable) race cars at 24hoursoflemons.com.

3 POWER TOOL DRAG RACING

Did we mention there was danger? Unpredictable wrecks are a given when your race vehicle is a modified belt sander, bench grinder, or circular saw using blades for wheels. Competitors race head-to-head heats on a two-lane plywood track with 2x4 side rails, as spectators marvel at the acceleration and ferocity of DeWalts, Milwaukee's, and Makitas turned into demented dragsters. First made popular at San Francisco's legendary Ace Junkyard (youtu.be/R8spkUG1l6c), PTDR is another spectacular DIY event that became a favorite at Maker Faires.

To get the general vibe, watch Bre Pettis' classic *Make:* video at youtu.be/WLmsz5N88vg, then learn the PTDR way at powertooldragraces.com (old, unsecure site) and hazardfactory.org/power-tool-races.

4 TAMIYA MINI 4WD RACING

Kind of like slot cars scaled up, these four-wheel-drive 1/32 scale cars don't need a remote control — instead they race in their own lane on a giant track full of loops, jumps, and corkscrews. The sport is a Japanese import that's finding fans in the U.S. with Tamiya's easy snap-together DIY kits (some screws, no glues) and endless customization options. Grab a car for \$15–\$20 and then you can swap aerodynamic bodies, or upgrade motors, gear ratios, and tire compounds, to tune your mini racer like a pit pro.

Ask at your local hobby store to find races and tuners groups near you; for more community and a tuning guide, check reddit.com/r/mini4wd. 🏁

ACTION! ELECTRIC DOGSLED



POWERED POOCHES

DOGS YOUNG
AND OLD CAN
MUSH ANYWHERE
WITH A CUSTOM
E-DOGSLED

WRITTEN BY SAM FREEMAN

High-energy breeds are some of the most commonly surrendered dogs. People get them as puppies but are utterly unprepared for the amount of energy they expel. These dogs would be happy mushing a sled daily, but that's impractical for most owners. It's also physically demanding on humans, requires a whole team of well-trained dogs, and only works on snow.

But **Bill "WooFDriver" Helman's** pet Huskies are built for working hard and pulling weight, and he's determined to give them a satisfying experience. So he constructed an "electric dogsled on wheels." Aimed at working breeds but adaptable for all types, this hybrid e-dogsled allows senior dogs and senior humans to engage in long-distance exercise over non-snow terrain. Small dogs are invited too! He's taken out dogs as light as 12lbs, who benefit from using a bike tow leash to keep them away from the wheels.

Helman started mixing dogsledding and powered vehicles — DogMotoSports as he calls

it — almost 30 years ago. From bikes to ATVs, he's experimented with over 50 vehicles so far.

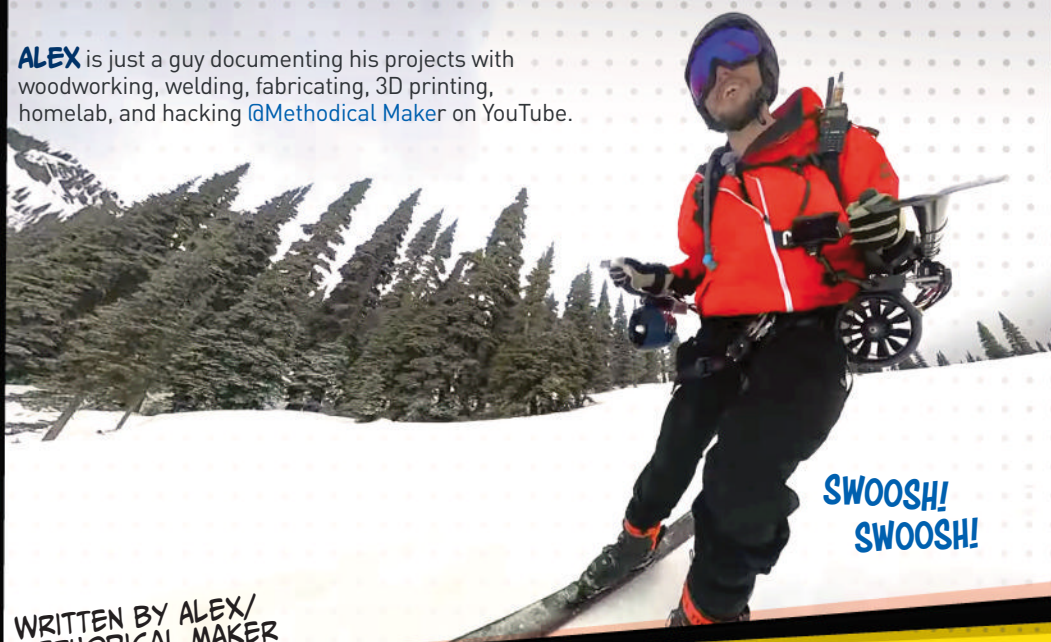
The current setup began life as a pedal-electric recumbent trike. He replaced the pedal arm with a 9-foot aluminum bar, wrapped in foam to protect the dogs. Instead of a slack gangline, this rigid beam lets the powered cart assist the animals and keeps untrained pups from pulling it off-course. Fixed to the arm are flexible harness rigs, commercially made for pulling scooters. A wireless flashlight is mounted in front to keep the light from blinding the dogs at night, and a ballast in the rear helps keep weight off their backs.

Though it moves slower than a dogless ebike, Helman has taken his e-dogsled on trips up to 30 miles around the East Coast. He isn't currently selling sleds, but invites others to build their own. Recommended components, and lots more about the sport, are listed on his main site at dogmotosports.com.

As they say, an active dog is a happy dog. 🐾

Bill Helman

ALEX is just a guy documenting his projects with woodworking, welding, fabricating, 3D printing, homelab, and hacking @Methodical Maker on YouTube.



WRITTEN BY ALEX/
METHODICAL MAKER

SKIING ON JET POWER

BEING IMPRACTICAL DOESN'T MAKE IT IMPOSSIBLE

I grew up watching inventors like Colin Furze strap jet engines to all sorts of things. Maybe this is why I've always had a fascination with speed. As soon as I had enough confidence to go fast downhill on skis, I wanted to make something to push the boundary.

I settled on using the E-jets Jetfan-120 ECO with an HET 800-73-590 motor, an electric ducted fan (EDF) for R/C jet airplanes that produces 20.5lbs of thrust at 6.7kW. A pair of them, and I planned to give them a whopping 8kW per motor. That's just shy of 11 horsepower per EDF — in other words, the equivalent of a Honda Grom motorcycle under each arm!

The battery needed a massive 196 cells, spot welded with custom copper and nickel interconnects to handle the insane current draw. The throttle is a knockoff Wii Nunchuck, and the backbone of the project is extruded 3030 T-slot aluminum with a custom-milled aluminum mount, all attached to me with a climbing

harness and parts salvaged from a physical therapy arm brace.

I immediately respected the jets when the ESCs chirped to life. They elicited a mixture of excitement and fear — the same feeling you get as you lower the restraints on a roller coaster. I could tell a long burst of throttle could have broken my own personal speed record of 68mph.

I also tested towing my safety buddy. He ate more than his daily recommended amount of atmosphere from the jet wash, but seemed happy he didn't have to work to cross the cat tracks.

I had a blast bringing the idea to life. It's heavy, loud, and very impractical. But that was never the point. This was a wild idea that lived in my head for years. I just needed to know if it could be done. Also, I learned that 16 kilowatts of thrust feels incredible. I consider that a win.

Read the whole story at makezine.com/article/drones-vehicles/rockets/skiing-on-jet-power. 🚀

FLAME VORTEX

**BUILD A MESMERIZING
6-FOOT FIRE TORNADO
FOR FESTIVITIES!**

WRITTEN AND PHOTOGRAPHED BY TIM DEAGAN



TIM DEAGAN makes, breaks, and collects things in Austin, Texas. He loves the experience of using software to breathe life into hardware, using any microcontroller he can get his hands on.



MAKING FIRE DANCE

I have a lifetime relationship with fire. Both the beauty and the danger constantly excite me, making me want to control it and delight in its chaos. Recently, I've been exploring flame effects that are more mesmerizing than full of "shock and awe." Making fire dance, spin, and writhe was the goal of this project: a portable flame vortex.

Flame vortices or tornadoes are almost impossible to look away from. I had first seen them at brush fires in my youth and fallen in love. Over the years, I've seen a variety of approaches for making them on demand, but few designs were easily portable or able to run continuously for hours. This project could be the world's coolest fire pit on a deck, or a crowd-pleaser at a campout or festival. (Please follow all appropriate permitting and NFPA standards if required by the authority having jurisdiction.)

WHAT IS A VORTEX?

The term *vortex* refers to a fluid, typically air or water, rotating around an axis and stretching out in some direction. In nature, this could be an eddy, tornado, cyclone, waterspout, hurricane, or other fluid rotation.

Two factors come into play for all these phenomena. The first is a source of **rotation**, and the second is a source of **lift**. The lift factor is what stretches the rotating material into a vortex. These two forces differ depending on the type of event. A hurricane relies on Coriolis forces for rotation, and convection from ocean heat for lift. A tornado uses wind shear for rotation and updrafts for lift. Most waterspouts result from surface convergence of winds and eddies as sources of rotation, and weak convection from warm water as the source of lift.

TIME REQUIRED: A WEEKEND

DIFFICULTY: INTERMEDIATE

COST: \$300-\$450

MATERIALS:

FUEL SYSTEM

- **Metal pie pan, 9"** or equivalent
- **Metal disc, 3"-4"** as thick as a coffee can or thicker
- **Pipe adapter, brass, ¾" male flare to ½" male pipe thread (NPT)**
- **Cutoff valve, ½", gas rated** Look for "WOG" (water/oil/gas) on the handle or body.
- **Pipe nipples, black iron, ½": 18" (1) and 3" (1)**
- **Pipe elbow, 90°, ½"**
- **Floor flange, ½"**
- **Adjustable regulator, high pressure** 0psi-5psi or higher, ideally up to 10psi
- **Propane hose, high pressure, with ¾" female flare fitting** ideally integral to the regulator
- **Portable propane cylinder, 20lb (BBQ)** or larger
- **Teflon tape, gas rated, or pipe dope**

AIR SYSTEM

- **Register boots, 14"×6"-8" diameter (2)**
- **Metal roof flashing, 14" wide, 10' roll**
- **Angle brackets (4)**
- **Round adjustable 90° elbows, 8" diameter (2)**
- **Flexible metal dryer duct, 8" diameter, 5' lengths (2)** You can cut a 10' length.
- **Fans (2)** providing a total of greater than 2,000cfm
- **Aluminum foil duct tape**

STRUCTURE

- **Metal disc or square, 28" or larger** for the base plate
- **Cinder blocks** or nonflammable stand of your choice

TOOLS:

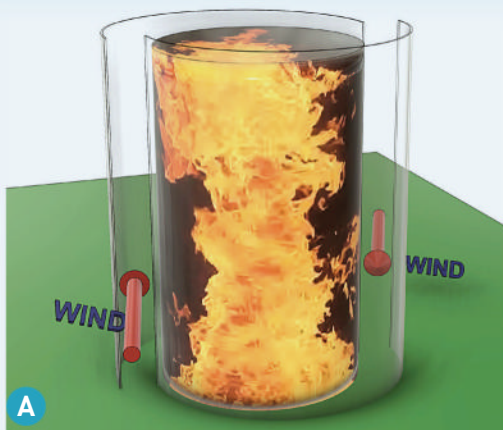
- **Shears** for sheet metal
- **Drill and drill bits**
- **Pipe wrench**
- **Pop rivet gun (optional)** but recommended



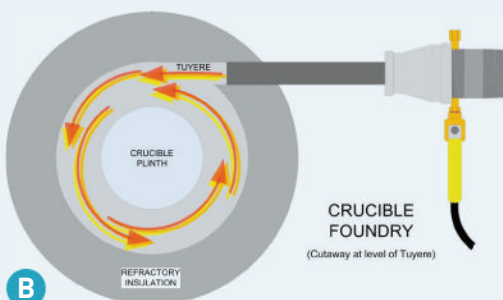
Vortices in nature: EF3 tornado in Gary, South Dakota; Cyclone Catarina seen from the ISS; waterspout over the Peace River, Florida.

[tornado] Wikiwiltz, CC-BY-SA-4.0 ; [cyclone] NASA; [waterspout] Punta Gorda Police Department

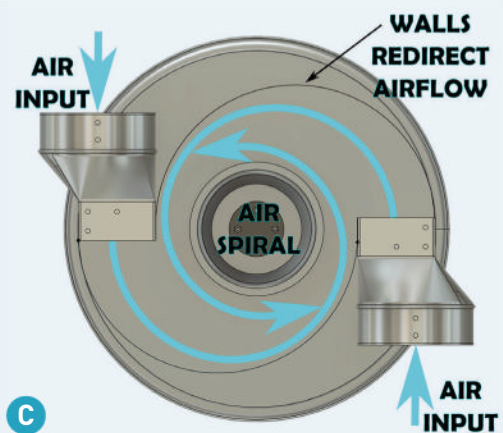
PROJECTS: Portable Flame Vortex



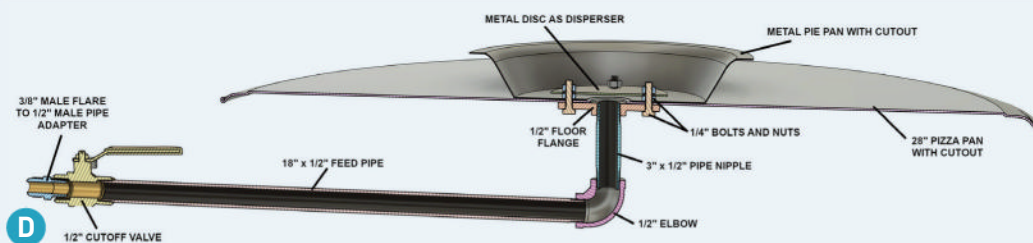
Tangential air flow from wind.



A furnace tuyere.



Tangential air flow system.



Propane vapor feed cutaway.

Fire vortex projects generally rely on the heat of combustion for lift. Fans or passive techniques for directing wind serve as the source of rotation. Many flame vortices use two offset half-circles of a transparent material to catch wind and create the desired flow (Figure A).

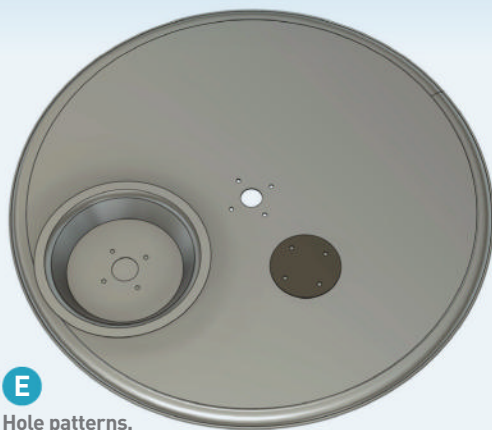
DESIGNING THE VORTEX

Given my lack of formal fluid dynamics knowledge, I needed design criteria that didn't rely on finicky tolerances. My vortex effect needed to work under a wide variety of wind conditions, fuel flow volumes, and air flow volumes. It needed to scale the flames from one to 10 feet high, depending on circumstances. Other than the fans, the components needed to be weatherproof enough to live outside. Transport and setup needed to be minimal. My design decisions reflected these requirements.

Rather than relying on unpredictable winds or using a wide circle of box fans to create the tangential air flow, I wanted to use the approach commonly found in propane crucible furnaces: a **tuyere**. This approach mounts a torch into the edge of a cylindrical furnace and causes the flame to rotate around the crucible (Figure B). I had noticed that these foundries often create a small flame vortex when operating without a lid.

Instead of injecting flame tangentially, my flame vortex injects air from ventilation fans. This allows the use of readily available fans and ducting components to create the spinning air flow inside the well of the effect (Figure C).

Introducing fuel vapor from any direction other than the bottom adds complexity and risk (since all other directions would effectively pass the fuel feed through the flame itself.) A bottom feed is fairly easy to plumb and to direct into the main combustion area. Once the vapor enters



E
Hole patterns.

the bottom, it's useful to spread it out to allow a larger volume of air/flame to be moved by the fans. To do this, a small disperser plate is mounted just over the incoming vent. A pie pan with an upturned rim surrounds the vent and redirects the vapor upward (Figure **D**).

BUILD YOUR FLAME VORTEX

The specific parts described and their absolute sizes are not crucial to this project. A larger or smaller base, $\frac{3}{4}$ " instead of $\frac{1}{2}$ " plumbing, different fans, or alternate plumbing configurations are all viable within some general constraints. I've been pleasantly surprised how forgiving this build has been. As long as you have a good idea of what the two systems (propane vapor feed and tangential air flow) are trying to do, you can achieve an awesome vortex with a range of different builds.

1. BASE AND FUEL DISPERSER

To construct the vortex, begin by using the floor flange as a template for the holes needed in the bottom plate, pie pan redirector, and top disperser plate. Center the floor flange and use it as a stencil to mark the center hole and the bolt holes on the bottom plate and pie pan. Mark only the bolt holes on the disperser plate (Figure **E**).

Drill the bolt holes with an appropriately sized bit, likely $\frac{1}{4}$ ". Make the center hole the same size or larger than the pipe connected to the floor flange, but not so big that it cuts into the bolt holes. A hole saw is ideal, but other methods will work (chain drilling, starter hole and jigsaw, etc.). This hole doesn't have to be perfectly circular as long as there's clear passage above the pipe.

MATERIAL SAFETY NOTES

Since this is a flame effect, the materials used must be nonflammable. In my testing, I did not record any part hotter than 400°F (205°C) after a couple hours of continuous operation. These temps were in the area of the burner vent and pie pan redirector. Due primarily to the constant injection of cool air by the fans, most parts stayed at a fraction of this temperature, not heating beyond 150°F (65°C).

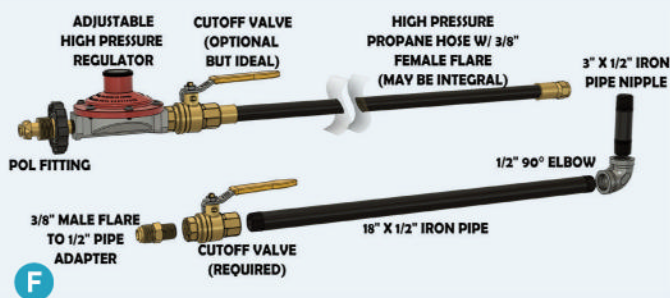
In my design, I use galvanized steel ducting for the air entries and galvanized roofing flashing for the curved outer shell. These parts have constant air blown upon them during operation, providing active cooling. Even after running my vortex for 7 hours continuously, I noted no melting or burning of the zinc coating [e.g., yellowish-green smoke or white powdery dust.] As a telltale, I left the manufacturer's paper sticker on the inside of my galvanized sheet metal, facing in toward the flames. In over 20 hours of burning, the paper hasn't even turned brown. This confirms my spot checks with an infrared thermometer showing that the material is not reaching temperatures of concern.

However, it is important to be aware of risks and plan accordingly. *Zinc can begin to emit fumes at 392°F (200°C).* Zinc fumes can cause flu-like symptoms when inhaled in sufficient quantity. Heating zinc should always occur in a well-ventilated area. The vortex, which should only be operated outside in a safe area and has constant high-volume airflow, provides a tremendous amount of ventilation. However, if this margin of safety feels unacceptable, non-coated material should be substituted for galvanized material.

The most common substitute for galvanized steel sheet metal is aluminum. Aluminum does not emit fumes but can lose significant strength at 572°F (300°C). The guide walls and ducting, as noted above, receive active cooling from the fans and should be OK, but they're thin and they aren't incredibly strong. The base plate and disperser components can approach 700°F (370°C) with extended operation (mine did after 8 hours on a hot Texas night), so don't use galvanized steel or aluminum for these.

This device is an experimental test platform for creating flame vortices. Temperatures should be monitored with an infrared (contactless) thermometer so that safe ranges are not exceeded. Uncoated sheet steel can be substituted, though that adds some fabrication considerations. Monitor any solution you adopt to avoid problems.

PROJECTS: Portable Flame Vortex



Assemble as shown in Figure D. Run the bolts through the floor flange into the bottom of the base plate. On top of the base plate, place the pie pan and a set of nuts to bolt it down. These nuts serve as the standoff for the disperser plate, which comes next. Thread a final set of nuts to hold the disperser plate in place.

2. GAS PLUMBING

The plumbing system has two parts (Figure F): the feed from the propane cylinder (top) and the feed into the flame effect (bottom). The feed from the cylinder may be assembled or purchased as a complete component. It needs to include, at a minimum, a high-pressure adjustable regulator with a standard POL (CGA 510) connection for the propane cylinder, and a hose with a 3/8" female flare fitting at the end. This effect is awesome at 10psi or less, so any adjustable regulator offering at least a max pressure of 10psi will work great.

Having a gauge or an additional cutoff valve is especially valuable, but an "all-in-one" cylinder adapter, regulator, and hose with fitting will work (Figure G). Avoid Acme fittings (shown at left) — the kind you can hand-tighten onto the outside of the propane cylinder valve — unless you want to restrict yourself to 20lb BBQ-style cylinders. If you want the option of using larger cylinders, be sure to get a POL-style valve that threads inside the cylinder valve (shown at right).

The feed line into the effect begins with a way to attach the hose. Flare fittings don't require Teflon tape or pipe dope; they mate together by simply screwing them tight. This allows an easy disassembly point. The 3/8" flare is the common size used with propane hoses, so we use a male 3/8" flare to 1/2" male pipe adapter that threads into a 1/2" cutoff valve. Do use yellow Teflon gas tape or

pipe dope to cover these threads.

On the other side of the cutoff, an 18" length of 1/2" pipe connects to a 1/2" 90° pipe elbow, followed by a 3" x 1/2" black iron pipe nipple (Figure G). This 3" nipple threads into the floor flange. Because this final section of plumbing is open to the atmosphere, these connections don't need tape or pipe dope, but it doesn't hurt to include it.

3. AIR SYSTEM

The airflow system consists of 8" register boots with 14" x 6" outlets that are attached to the base plate facing opposite directions. Any method of securely attaching these to the base plate works, but I believe the easiest is pop rivets, ideally steel. Sheet metal fabrications like this can be surprisingly flexible, so I recommend adding a stiffening component, such as a rigid plate or some angle brackets along the inside bottom of the outlet. Angle brackets are great since they're available in different sizes and can stiffen the upright walls as well (Figure H). If your pop-rivet head is too small for the hole in your bracket, you may need to use a longer rivet and add a washer.

Mount both boots on opposite sides of the plate, facing opposite directions. Then measure from the outside edge of one boot's outlet to the inside edge of the opposite boot (Figure I). This is the diameter of each of the two half-circles which will form the walls. To convert this to the necessary length of 14" roof flashing, multiply your measured diameter times pi (3.14 will do). Then add 4" to provide 1" of overlap for riveting the flashing to the sides of the register boots. This is the total length of flashing needed; cut it in half to provide the two half-circles.

Hold one of the half-circles in place, allowing an inch of overlap against the boot edges, and

make sure that the circle formed doesn't extend outside the base plate. It's not a big problem if there's a slight gap at the bottom or edge; we're not going to seal these walls to the base plate. I tested with a small gap at the bottom, and it doesn't make a noticeable difference. The moving vortex air can actually entrain outside air along a gap at the bottom and draw it into the spiral.

For fans, I used 1,560cfm (cubic feet per minute) 8" ventilator fans. Other solutions are possible, but it's hard to find inline duct fans with that kind of output. It's possible to scale the effect down from an 8" airflow plan to a 6" or even 4" design, but the corresponding size of your flame vortex will decrease as well.

To connect air ducting into the register boot, I used an 8" adjustable elbow that can be configured as straight-through or at an angle up to 90°. I used 8" flexible metallized clothes dryer ducting hose to connect the fans' output to these 8" elbows. This can be helpful when tuning the airflow input, which I'll describe later. I use aluminum foil duct tape to fix the elbow into the boot. The dryer duct attaches to the other end of the elbow with a large hose clamp (Figure J), typically provided with the dryer duct.

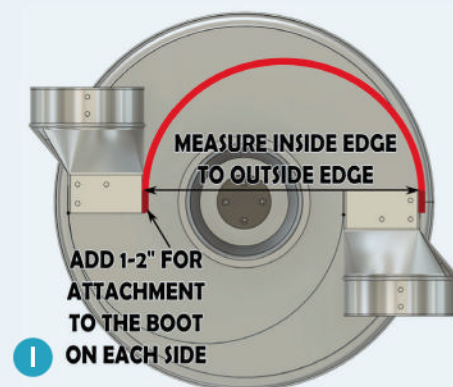
Surprise: The 8" ducting hose and the 8" fan outlet aren't the same diameter! The inside diameter of the duct I bought is $\frac{1}{4}$ " larger than the internal diameter and $\frac{1}{4}$ " smaller than the external diameter of the fan I'm using. An adapter is needed. I 3D printed one (Figure K), but a simple alternative is to cut a 7"x28" section from your remaining roof flashing. Roll this into a circle and fit it into the end of the hose with a couple of inches sticking out (Figure L). Tighten the protruding end of the rolled flashing until it fits into the output side of the fan (having removed the fan's output safety grill.) Use copious amounts of aluminum foil duct tape to hold it all together.

The effect needs to stand at least 12" off the ground. Cinder blocks or an alternative nonflammable stand should be placed under the bottom plate to assure a stable platform.

SPIN UP A FIRE TORNADO!

OPERATING THE FLAME VORTEX

Once everything is put together, running the vortex is very simple:



PROJECTS: Portable Flame Vortex

1. With the cutoff valve closed, open the cylinder valve and adjust the regulator so that it is completely off.
2. Light a rolled-up piece of paper and place it in the pie plate area. (Don't use a big roll of paper, you don't want cinders coming out in a geyser!)
3. Open the cutoff valve and slowly increase the pressure on the regulator a small amount so that the fuel vapor ignites.
4. Turn on your fans.
5. Slowly increase the pressure on the regulator and watch the fire spin!

Shutting down is very easy:

1. Close the cylinder valve.
2. After the fire is extinguished, close the cutoff valve.
3. Leave the fans running for a few minutes to cool the effect down, and then shut them off.

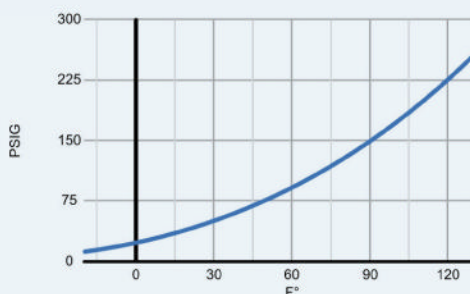
BURN RATE

Operating my vortex at 2psi–5psi to create a 5'–6'-tall vortex used approximately 6lbs–8lbs of liquid propane per hour (declining once the internal pressure in the cylinder dropped below my target pressure.)

The specific burn rate depends on temperature and pressure. As vapor is drawn from the cylinder, the liquid will cool as it uses energy to boil off more vapor. The reduced temperature results in a lower vapor pressure available from the cylinder. So, the longer you run, the less pressure and vapor you'll be able to draw. Additionally, the ambient temperature, which is how the cylinder heats back up over time, factors in. If it's cold outside, the available pressure drops proportionally, either limiting the max pressure or accelerating the auto-refrigeration process.

If you want to run the effect for more than 20 minutes at a time, you'll need to use larger cylinders, or swap multiple 20lb cylinders. A 20lb cylinder will freeze up and lose pressure (until it can rest and warm back up) before it uses more than a quarter of its propane. A 100lb cylinder can run for a couple hours before it is too cold to be effective (assuming an ambient temp that's at least above freezing) due to its larger thermal inertial mass.

If you're anything like me, you're going to want



Propane temperature/pressure curve.

to increase the pressure from the regulator to see what happens. The fire will get bigger! But you will also increase your flow rate and use propane faster. Eventually, the cylinder will get so cold that your max pressure is 1psi–2psi. You'll know — there will be a quarter-inch of ice forming around the cylinder, and the vortex will shrink to 2'–3' tall.

TUNING YOUR FLAME VORTEX

There are a few options for tuning and maintaining the vortex effect.

- Check the intakes of your fans to make sure you feel an intake of air. If something is restricting the airflow, you'll feel air blowing out of the intake.
- When the effect is not lit, hold your hand just

in front of the outlet of the register boots. You shouldn't feel much air blowing above the rim of the boot and walls. If you do, reorient the adjustable elbow so that the air stays mostly inside the walls.

- Wind will disrupt the vortex. Operating in an area where a fence or other structures (not too close!) serve to shelter the effect can help. Constant wind over 3mph–4mph makes it hard to operate effectively, but the vortex is surprisingly resilient in occasional gusts below 7mph. It will lose coherency, but it's a joy to watch it spring right back.
- The roof flashing can get bent or dented. For the most part, this isn't critical. But if it gets so bent that it no longer forms an effective curve, you can often bend it back into shape by hand.
- Cover the device when not in use. Rain can drain into your plumbing feed and cause rust.

SAFETY CONSIDERATIONS

Working with, dare I say playing with, fire requires careful consideration and attention.

- Do not operate the vortex within 10' of anything flammable. Don't operate under trees or power lines. Obey your local fire regulations.
- With the cutoff valve closed, check the fuel system for leaks using soapy water. Tighten to eliminate any leaks found.
- Make sure the effect is stably placed at least 12" above the ground, with no leaves or grass that can come in contact.
- Always have a ready means of fire extinguishing handy. A garden hose will do, but a fire extinguisher (sodium bicarbonate or pressurized H₂O) is great.
- Don't let people stick their hands or heads in the fire (you'd be surprised, those people are out there). Don't let folks get closer than they would to a bonfire of a similar size. The wind will blow the vortex around, and it will try to kiss people. Pay attention.
- Make sure your propane cylinders are stable and can't be knocked over.
- Make sure your fans' electrical cords are placed where people won't trip over them.
- Assert control over your cylinder, regulator, and cutoff valve(s). Don't let people play with or near them.

- Don't leave the effect unattended by a responsible person who knows how to shut it off when it is lit.

IDEAS FOR MODIFICATIONS

There's more than one way to build a fire tornado (check out Caleb Kraft's project in *Make*: with a different approach: makezine.com/projects/fire-tornado). But my vortex design is easily portable, reliable, and flexible if you want to make improvements.

- If you build a smaller version of the effect, you could put **in-line duct fans** directly into the inputs of the register boots. These typically don't push a lot of air (not nearly as much as ventilator fans) but could make for a smaller build, resulting in a smaller flame.
- A more permanently located effect would benefit from installing a **remote igniter** from a furnace or grill into the pie plate area. Much like the fuel feed, this would be best installed from underneath the base plate.
- If you plumb **multiple inlets** into the feed pipe (additional flare fittings and cutoff valves using plumbing tees) you can easily swap tanks when one gets too cold, or connect different tanks/regulators at different pressures, allowing a quick burst of "big" tornado action.

When built and used with safety in mind, the flame vortex is an effect that draws people like, well, moths to a flame! Because it runs continuously for long periods, people will hang out and become mesmerized, chatting with one another, staring into the spinning flame. It is one of the most social flame effects I've ever run.

Enjoy! 🌀



Box fan fire tornado built by Caleb Kraft.

SIGHT, SOUND, AND SNORKELING

EXPLORE UNDERSEA PERCEPTION BY
TRANSMITTING SOUND WAVES THROUGH
MODULATED LIGHT WAVES

WRITTEN BY LEE WILKINS



DR. LEE WILKINS is an artist, cyborg, technologist, and educator based in Montreal, Quebec, a board member of the Open Source Hardware Association, and the author of this column on technology and the body and how they intertwine. Follow them on Instagram [@leeborg_](#)

Salima Punjani

In the 1930s, explorer William Beebe conducted a series of undersea experiments in order to observe and document deep sea creatures.

He descended into the ocean off the coast of Bermuda in a giant metal sphere called the Bathysphere, with a single tiny window to observe the ocean floor. He communicated what he saw through a phone line connected to the surface, where artist Else Bostelmann drew what he described. Her paintings were truly amazing, much like the creatures Beebe saw.

As someone who can't see most things, I've always been fascinated by this story. I've been thinking about its relevance for low-vision people, because we often rely on description in some form or another. It's only been in the past few years that I've started to experiment with description tools, such as audio description in video media, alt text description for images on the internet, or simply asking people to describe things specifically rather than just not knowing what they are.

While Beebe was trying to catalog and identify species of underwater creatures, Bostelmann was trying to capture their essence in her paintings. They are not necessarily scientific images; they depict scenes and capture dynamics between creatures. I think both elements are important when providing description, but audio descriptions tend to focus on one and neglect the other. I've been creating a series of description-oriented works around this concept, including this one, a kind of DIY diving bell.

EXPLORING UNDERSEA PERCEPTION

It's been quite a while since I've exhibited my own personal work. I've had work in galleries but it's usually assisting someone else, or working with a group, or being part of a collective effort. I love that stuff, but this spring I had the opportunity to showcase a conceptual piece that I've been working on all alone for the last year. My most recent piece is called *A Guide to Snorkeling*, and it's a work about a speculative world where technology has evolved differently, focusing on different senses. It's also an exploration of snorkeling and looking at undersea creatures, which I did last year at Dinacon (dinacon.org). I wrote about this experience on Medium ([medium](https://medium.com/@aleeborg_/752a58daaa4e)).

TIME REQUIRED: A WEEKEND

DIFFICULTY: INTERMEDIATE

COST: \$1,500

MATERIALS:

- Mini audio amplifier boards, PAM8610 chip such as Amazon B07PDGDKRW
- Audio recording sound module, 16MB XLW model 1653, Amazon B0C491SSSK
- High-power LEDs
- Auxiliary audio cable
- Power supplies: 12V and 5V
- Solar panels
- Speakers
- Wire
- Acrylic sheet for laser cutting
- Sign stand-off screws for glass or acrylic signs

TOOLS:

- Laser cutter
- 3D printer
- Soldering iron
- Drill

[com/@aleeborg_/752a58daaa4e](https://medium.com/@aleeborg_/752a58daaa4e)), which feels a bit vulnerable to share in this column, but have a read if you want to learn a bit more about me as a person!

Bear with me for a moment while I diverge slightly from our usual content into a more artistic description. In this piece, the viewer can listen to different audio descriptions of fish and underwater creatures by physically moving a listening device around different sources of modulated light that each carry their own audio signal. Similar to exploring the ocean visually, the viewer navigates audio spatially and mediated by the light through sound, rather than light through vision.

There's a classic term in traditional artwork called *light-based media*, meaning photography, video, lithography, cyanotype, etc.; more contemporarily, you can think of screens, AR/VR, and projections. Either way, it refers to technology that's primarily visual. We usually imagine light as a tool for viewing, and almost never as a tool for hearing, but it doesn't mean it can't be used that way!

Light-based media is the way we experience

PROJECTS: Squishy Tech

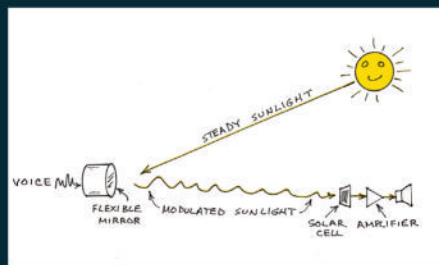
so, so much of the world, and is a cornerstone to almost all technology. In this piece, I'm reimagining a future where light-based media is auditory — a speculative future that relies on other senses, and ways technology could have diverged if, for example, vision was not a primary sense. I collected the recordings in this work from people at Dinacon, who graciously described to me sea creatures they saw while snorkeling so that I could experience them. I sent people into the water with sound recording modules inside a waterproof bag and asked them to save a description of a single fish. Some of the recordings in this work were re-created after the fact, and some were not.

The piece was exhibited at the HTMLles festival at Ada X in Montreal in spring 2026. Thank you to Deb VanSlet, Salima Punjani, Kyle Chisholm, Don Undeen, Gretchen McCulloch, Alex Bachmeyer, Dounia Bouzidi, Concordia University CUPFA, Radio Snack, and the entire Ada X and HTMLles teams for making this specific exhibition happen; and to those who helped forge this work in Bali: Jay Bond, Marie LeBlanc Flanagan, Xindi Kang, Paula Te, Andy Quitmeyer, Isaac Clarke, Anna, Sid Drmay, Jan Maartan, Bri Johns, Alex Hornstein, Sea Communities, and Gumball.

SENDING SOUND THROUGH LIGHT

Now back to the tech. This artwork uses a pretty cool circuit that sends audio wirelessly through light. I first encountered the circuit 15 years ago when my friend Rhys Mendes showed me a project he made: a silent dance party that used flickering light bulbs and LDR light sensors. People were wearing helmets with very simple voltage divider circuits and headphones on them and dancing around silently. This was pretty cool because they could move throughout the space freely and hear different songs based on how the light was hitting their sensors.

I've experimented with this circuit a few times since then, at a 2015 exhibition called "The Orbs" at Site 3 makerspace in Toronto, where people used futuristic-looking devices to listen to conversations being communicated through an illuminated orb, and again in 2017 at the EDIT festival, where I had historical audio of women in aviation telling their stories through light.



PHOTOPHONE ME

Another example of this circuit is the Photophone by Forrest Mims from *Make: Volume 78*, which lets you send your voice via a sunbeam in a clever arrangement of mirrors and solar panels. You can build it at makezine.com/projects/amateur-scientist-listening-to-light.

Each edition of this circuit used slightly different technology, but always using fluctuating light to encode and decode audio signals.

SPEAKING OF SPEAKERS

What is a speaker, anyway? This question is at the core of why I think this circuit is interesting. I explored this in my column in *Make: Volume 84* about soft speakers: basically speakers are made of a coil, a magnet, and a membrane that creates vibrations. A signal is sent through a coil around the magnet, causing a pulsing effect that creates physical vibrations in the membrane. These vibrations move through the air to create sound, and your ears pick up the vibrations and decode the message.

Instead of using the audio signal to vibrate a membrane, in this circuit I'm using the signal to pulse a light. But you can't decode that with your eyes. Instead, I use a solar panel which then produces a voltage that fluctuates at the same frequency as the light. The solar panel is connected to a speaker, and sound is produced! It's wildly simple, but feels really strange to experience.

In this work, each light source has a sound recorder module, an amplifier, and a bright LED. There are four listening modules that people can use to freely navigate, which are made of a solar panel and speaker (Figure A). The rest is just



some fancy acrylic and 3D printing, but I'll tell you how it all goes together!

TRANSMIT SOUNDSCAPES BY LIGHT

1. ASSEMBLE THE TRANSMITTER

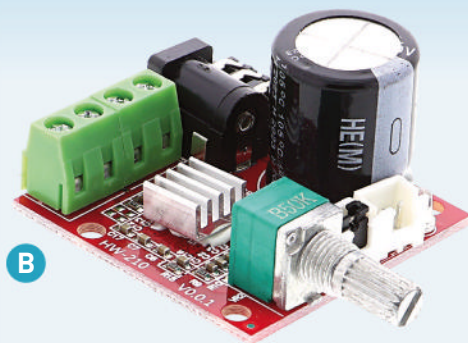
I used a simple audio recorder module to store sound files I recorded and play them back. There are a variety of options, but I chose one that was very cheap so I could get lots of them.

I modified the board by first removing the speaker and replacing it with an auxiliary audio cord so I could plug it into the amplifier. I then removed the battery and added a JST connector so I could connect it to the power supply.

The specific module I used was the XLW 1653 Sound Module, which allows you to do some playback configuration. By connecting the module via USB you can edit its `config.txt` file with different modes. I sent it to mode 4, which means as long as the button is pressed the file will loop. I then removed the button and used a jumper to make the connection, so that the button is "always pressed" and therefore the sound file is always looping. You can see the instructions at manuals.plus/ae/1005006761068667, which show all the different playback modes.

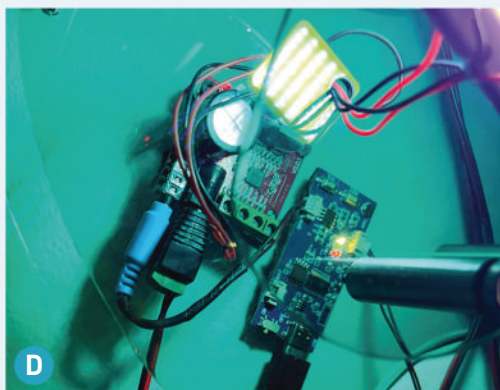
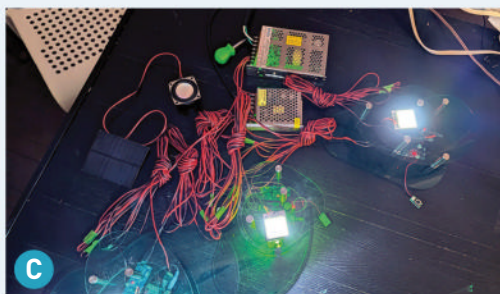
NOTE: If you're using a Mac with Apple silicon you may not be able to easily upload your sound files to this board. I had issues where the drive kept disconnecting, but that was solved when I used my 2018 Mac with an Intel chip.

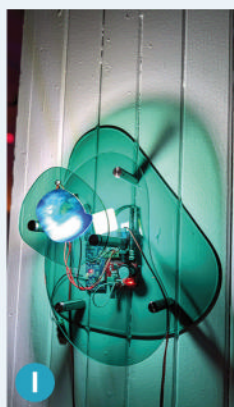
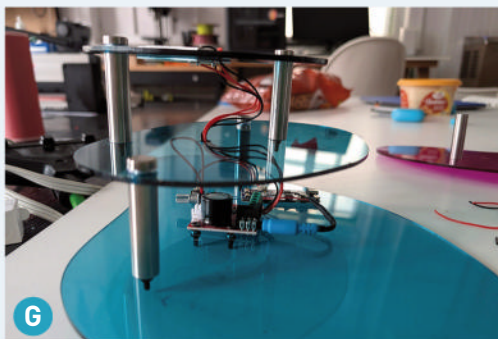
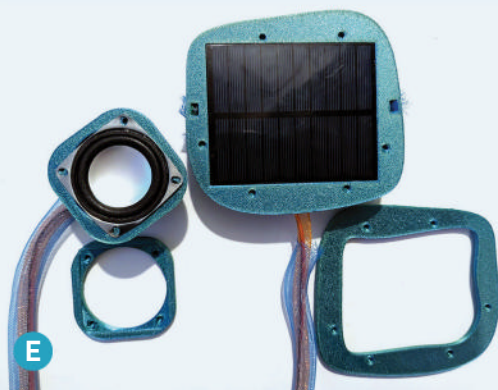
I then connected an LED to the left and right channel of the amplifier, exactly where your speaker would normally be connected. You can



use multi-channel audio if you want left and right channels to output different sounds, but I kept it simple with single-channel. You should also be aware that you need to jump the two connectors closest to the potentiometer for the amplifier to actually turn on (Figure B).

The other thing to note is that I had issues with sharing power supplies with the amplifier and XLW board. I'm not totally sure what happened here, and would love anyone's thoughts on this. I tried to use a 12V power supply for the amplifier with a buck converter to reduce the voltage to power the XLW board, but when I connected them with a shared ground, they both stopped working. I tried a bunch of different things, but ended up having to use two power supplies for this circuit (Figure C and D). I had other issues with





grounding and this amplifier too, which I'll outline below. Anyway, luckily the wire aesthetic worked for the artwork!

2. ASSEMBLE THE RECEIVER

The receiver is extremely simple. I used a 5V solar panel and connected it directly to the speaker. I know there could be some low-pass filters to clean up the sound, but honestly the raw nature of the recording felt important to the artwork!

I had some help designing 3D-printed enclosures that allowed both panel and speaker to be handheld (Figure **E**). The enclosure used a pin/socket system and M4 bolts to hold a hand strap. I also used some fabric tubing to cover the wires so it looked a bit cleaner. I printed with two-color filaments to match the aesthetic of the installation (Figure **F**).

3. LASER CUT THE LAYOUT

I designed the layout in Adobe Illustrator for cutting out flat pieces of acrylic. The design uses acrylic sign standoffs to hold each layer away from the one below, giving the electronics and light each a bit of space. Each design is three tiers: the base which has the bulk of the circuitry, a middle panel to cast a shadow, and the top panel that holds the LEDs. The standoffs were really great because they also allowed each piece to be easily screwed into the wall of the gallery.

I did test a few diffusion methods for the light too, but ultimately decided against using any. I used M4 machine screws to hold the electronics into the acrylic panels (Figure **G**), and mounting screws to put each module into the wall (Figures **H** and **I**).

4. INSTALLATION PREP

Once I had a working module, I created variations of the design to make different shapes. I also made some "filler" shapes without the modules (Figure **J**). I decided to just kind of wing it rather than over-plan the exact layout, so I also made very long wires for each module (probably longer than required) so I wouldn't have to worry about the final layout (Figure **K**).

When making gallery artwork like this, I always try to do most of the prep before I get to the actual gallery. I also pack a very extensive

install bag with every tool I've used throughout the production of the work, just in case something gets weird!

Since I had issues originally with the buck converter and shared ground, I ended up needing two power supplies. I put one on each side and used terminal blocks to connect everything together (Figure L). I leaned into this messy wire aesthetic!

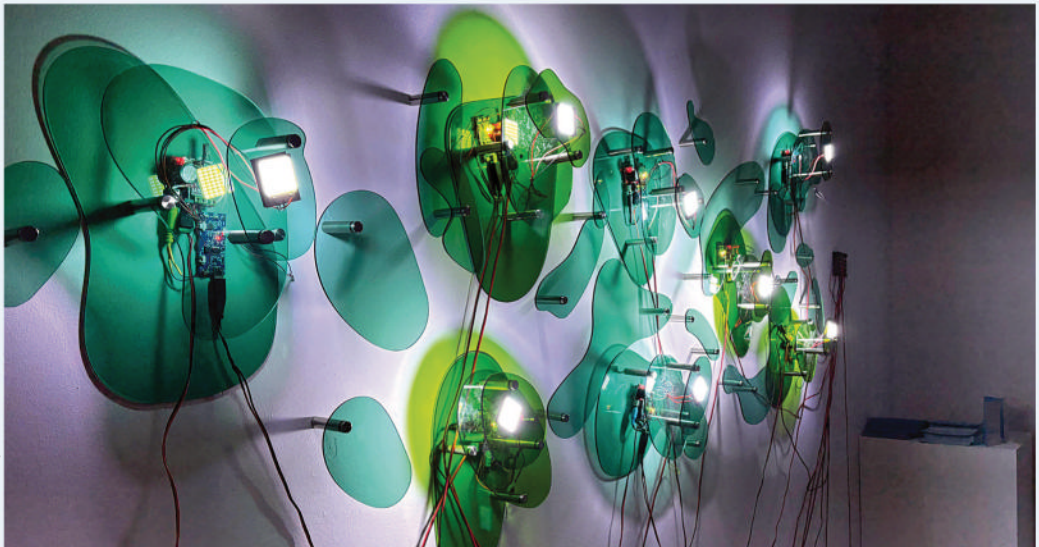
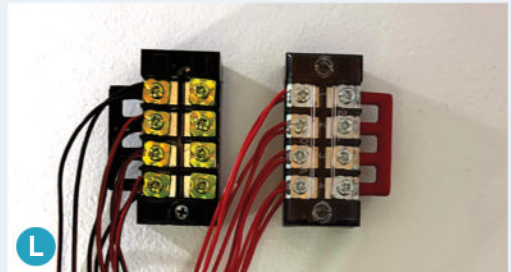
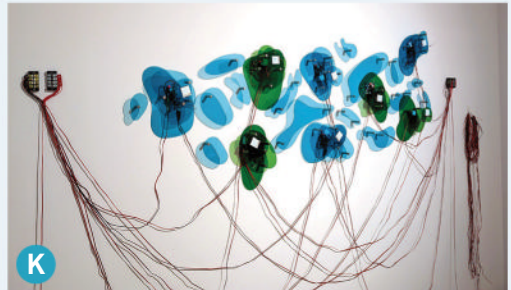
5. GHOSTS IN THE MACHINE

I tested each module individually, but I didn't get a chance to test it all together until I installed it at the gallery. This is where I experienced the second strange grounding issue I mentioned earlier. Once I had all the amplifiers connected to the same 12V power supply, the audio signals began to mix together. For example, I could hear the traces of other audio tracks even when I was just listening to a single light.

I ended up having to give each individual module its own 12V power supply, which was not ideal, but I ran out of time to test it! If you have any idea what's going on, feel free to let me know.

YOUR TURN NOW

I have had a ton of fun working with this circuit for years, and would love to know what you all create with it! 🎧



Salima Punjani

A DEVICE OF ONE'S OWN

WRITTEN AND PHOTOGRAPHED BY KATI

FREE YOURSELF
FROM SAME-Y
CONSUMER TECH
WITH A BESPOKE
CYBERDECK



KATI is a software engineer from Germany who works on Linux for mainframes. To compensate, she builds whimsical hardware projects and shares them online in the hope that her chaos inspires more chaos.

If you've been sufficiently online recently, you've probably come across a *cyberdeck* or two: small, computer-adjacent contraptions blinking at you from social media posts. They all have something in common: they look amazing, unique, and so very different from the sad, gray rectangles of most modern devices.

Apart from giving you the visual nerd cred you've always dreamed of, building your own cyberdeck is much more meaningful. In an age when planned obsolescence is considered a valid business strategy and tech companies casually mix up the concepts of "renting" and "owning," to build something yourself becomes a tiny act of resistance. You can modify it, personalize it, extend it, repair it (break it, and repair it again; been there). And somewhere between collecting hot glue burns and a switch from an old radio, you add something revolutionary in the time of AI slop: personality.

Fortunately, it won't require deep technical knowledge or a workshop full of tools to get your first deck running.

THE SOUL OF A PINK MACHINE

Like so many maker endeavors, this cyberdeck project was born from a number of frustrations colliding. It was 2020, and I wanted a tiny, laptop-like cyberdeck. But due to, well, a pandemic, commercial solutions were both too hard to source and too hard on my early-career budget. And as a young woman in engineering, I was increasingly tired of being told, implicitly or explicitly, that femininity and competence are somehow mutually exclusive. If I was going to build my own machine, I wanted it to be unapologetically girly, fiercely femme, and the brightest shade of Black Metal pink available.

The resulting PinkPad is neither the most powerful nor the most technically advanced build out there. It is, however, exactly the thing I wanted. For me, that happened to be a pink Arch Linux machine that survives both being stuffed into a backpack and my own clumsiness. Yours will almost certainly be something entirely different.

MAKE A WISH

For Step Zero, don't start with hardware, start with a question: What is the computer you wish



No one's going to see the zip ties when it's done.



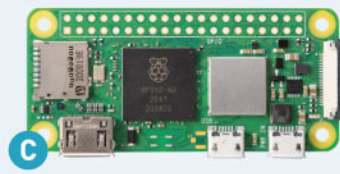
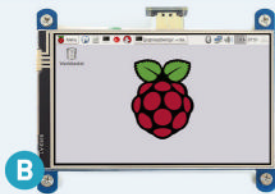
The opposite of slate gray.

NOTE: Before we get to the fun part, be aware that this isn't a step-by-step guide for a specific cyberdeck. Think of it more as a recipe to equip you with the ingredients every cyberdeck builder eventually has to decide on, sprinkled with a few "don't let this bite you the way it bit me" lessons.

existed? My creativity apparently only reached as far as "mutilating a toy to make it run Arch." But you might wish for a distraction-free writing machine, a health device that doesn't share your data with the cloud, or a retro gaming handheld for your childhood favorites. At this stage dream big, dream wild and whimsical. The actual hardware requirements will call you back to reality soon enough.

Most cyberdecks come down to the same components: a case, a small computer, a display, some input devices, a power supply, and software.

PROJECTS: Custom Cyberdeck Tips



These are the main decisions you'll make. Everything else arranges itself around them.

Whether you're assembling your parts Frankenstein-style or carefully planning everything from scratch, here are some considerations for each component of a first cyberdeck. None of them require specialized tools or supplies. A good knife, glue, and determination can carry you through the whole build.

The focus for a first build is always on the path of least resistance. Fear not, you can scale up the suffering with your later decks.

CHOOSE A CASE

The case is your project's showpiece and the thing that immediately sets the vibe of your deck (Figure A). You have a lot of freedom here: a vintage purse, a wall clock, even a plushie if you're feeling fancy. If you want it quick and (hopefully not too) dirty, have a closer look at your trash. That Amazon cardboard box or laundry detergent container? Prime cyberdeck material.

Your constraints here are straightforward: Can it fit my hardware, and does it support the project?

CHOOSE A DISPLAY

For a first build, choose a standalone display with standard connectors (Figure B). **HDMI** is your friend. Think Lego-like plug-and-play, not e-waste archaeology.

CHOOSE A COMPUTER

For beginners, a **Raspberry Pi** is hard to beat (Figure C). They come in different sizes and performance levels, and are easy to source both new and used. Most importantly, they don't just give you a small computer; they come with excellent documentation, countless tutorials, and an extraordinarily helpful community. Exactly what you want when you're getting started.

CHOOSE INPUT

There's a good chance your cyberdeck involves some amount of typing, which means you'll probably need a keyboard. Fortunately, the internet is full of options. Your job is simply to find the one that best matches your project.

Comfort is the main concern if you plan on typing a lot. Size matters if space is limited. One popular middle ground is the **Rii Mini** keyboard family: compact, rechargeable, and easy to integrate into many projects.



CHOOSE POWER

This is the part where you want to be least experimental during your first build. A beautifully boring solution is a **USB power bank**. Choose one that can provide the voltage and current your computer requires (for example, 5V and 2.5A for many Raspberry Pi models). The mAh rating roughly determines how long your deck can run.



CHOOSE AN OPERATING SYSTEM

Your tiny computer still needs an operating system. Fortunately, **Linux** is just as happy running inside a cyberdeck as it is on a server.

If you've chosen a Raspberry Pi, **Raspberry Pi OS** is the most beginner-friendly starting point. Flash it onto an **SD card**, insert it into your Pi, and you're ready to go. If you're feeling more adventurous, there are plenty of other Linux distributions waiting to be customized.

ASSEMBLE

Once you've gathered all the parts, your next task is fitting them together. Before brute-forcing everything into place, keep a few things in mind:

- Some parts need charging. Make sure you can still access their charging ports.

- Some parts need cooling, and you don't want to discover which ones by the smell of molten plastic. Let them run outside the case for a while. If they get noticeably warm, plan for airflow or a small fan.
- Your components need to be connected, and USB standardization at the moment is a crime against humanity. Make sure you have the right cables, adapters, and connectors.
- You may want to add things later. A USB hub can save you a surprising amount of frustration.
- File systems (for example on SD cards) do not enjoy being underpowered. If you frequently encounter file corruption, your power supply is a prime suspect.
- If you're new to electronics, don't jump right into full scavenger mode; extracting displays and similar components gets finicky fast. However, I encourage you to thrift things and ask your friends if they have a spare Pi. If sustainability isn't enough to convince you, then do it for your wallet.

YOU'RE NOT DONE YET

And after you've built your first cyberdeck, you get to enjoy one of its greatest features: a near-infinite supply of side quests.

There's always another completely unnecessary improvement that somehow seems essential at 3am. You'll keep customizing it, taking it apart, and upgrading it into things that progressively make others question your judgment.

Along the way you'll pick up (more or less) useful skills and fall down some rabbit holes. And if you decide to share your project with others, you'll gain something else: shared delusions. Cyberdeck builders are remarkably good at enabling each other's bad ideas. Small personal projects often turn into conversations and collaborations.

In the end, a cyberdeck does something a mass-produced computer can never achieve: become a reflection of the person who built it.

It's yours. 🍀

WORLD OF CYBERDECKS

There are as many expressions of cyberdecks as there are people who make them. If you can find it, you can hack it into a deck.



U.K. maker Andy Warburton's ESP32-powered GR3ML1N is light on power but boots quick and looks sick! andywarburton.co.uk/post/gr3ml1n-a-compact-handheld-cyberdeck-built-for-chaos



Will Haude of 3D Brooklyn designed a slick custom case and mouse for this all-in-one built around a Mac Mini. makerworld.com/en/models/1648861-retro-futuristic-cyberdeck



Amoretto's spooky DollPhone is built from a reprogrammed flip phone, and is a necessity to match their outfit during performances in Davis, California. instagram.com/reel/DYdS-H5B_0H

PROJECTS: Stop Motion Video Game

PUZZLING IT OUT

HOW WE BUILT A UNIQUE STOP MOTION VIDEO GAME

WRITTEN BY IVAN FISHER-OWEN AND BENJAMIN ORR



IVAN FISHER-OWEN is an animator and theatre artist in Limerick, Ireland. **BENJAMIN ORR** is a software and game developer in Pennsylvania, USA. Together they created *Éalú*, a video game rooted in physical craft.

FROM A TIKTOK EXPERIMENT TO A WILD IDEA

Ivan: It began with a moment of hubris, when I tried to use TikTok to tell an interactive, stop motion–animated tale 30 seconds at a time. Using a wooden clockwork mouse I had created for Will Wood’s music video “Tomcat Disposables,” I animated a short clip of the mouse in a tiny room with two doors and a hamster wheel, and invited viewers to suggest what happened next. Things didn’t go as planned — most viewers didn’t engage with the story as I hoped.

Being new to TikTok and out of touch with social media, I felt apprehensive, unable to understand the algorithms that drove TikTok as I interacted with it. I wondered how regular use might lead to strange or even harmful outcomes. I felt like a mouse trapped in a dangerous maze, and this realization inspired me to sketch out an interactive experience called *Éalú* where players could guide a mouse through a maze representing these incomprehensible systems.

The goal of *Éalú* (Irish for *escape*) would be for players to find an exit for the mouse, but the maze would tempt them to dwell inside longer — perhaps even draw them toward darkness. As a counterpoint to the technology it would comment on, my vision was for the experience to be carefully hand animated, frame by frame.

BUILDING A VIDEO GAME LIKE A PHYSICAL ART PIECE

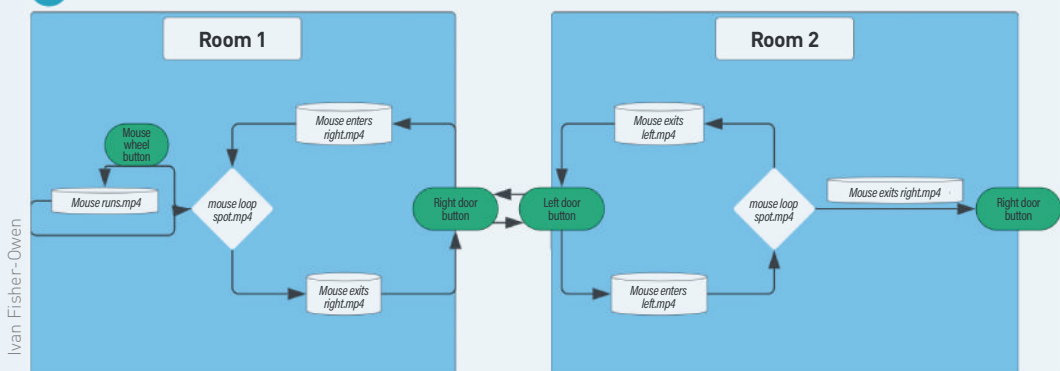
Ben: Knowing this wasn’t a one-person project, Ivan contacted me because of my experience working on game dev projects. The strange pitch he made was to create a stop motion game

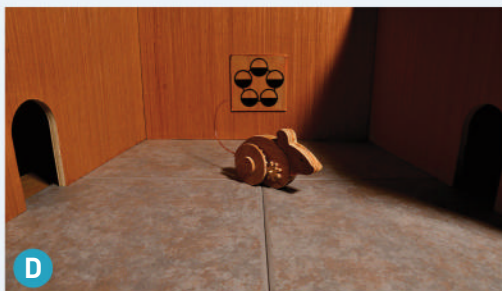
without using a sprite for the mouse protagonist. Instead, every possible action the mouse takes in the game would be hand animated and stored as video clips. The game’s back-end would seamlessly sequence these clips based on player input, essentially creating a sprawling FMV (full motion video) game. Also, there was no funding to create the game! I thought this approach sounded crazy, but was excited about the challenge, and so we got to work.

Our first step was a feasibility test. I designed a simple three-room proof of concept where our mouse could traverse rooms, run inside a wheel, and solve a logic puzzle (Figure A). Ivan set about creating the animations and I built the back-end architecture in the Unity game engine. The goal was to generate something that felt more like an interactive silent film or puppetry theater than a normal video game. To achieve this, Ivan created the set, props, and puppet all from wood using CNC tools, and I ensured that there was no heads-up display, mini map, or anything overlaid on the screen. The objects and buttons players could click on were designed to be intuitive and seamlessly integrated.

To my surprise, our proof of concept worked surprisingly well! It gave us a large morale boost and a strong sense of the time commitment needed to create a single room of the maze. My work in Unity and Ivan’s work on sets, props, and hand animating the visuals would be quite time consuming, so we knew we had to set our project scope very clearly and stick to it. Staying organized was essential due to the massive number of animation clips we’d need to sequence.

A ÉALÚ PROOF OF CONCEPT FLOWCHART





an alternate life as the center of an ad hoc stop motion studio (Figure F). I happily spent hundreds of hours in the shed, in the dark, incrementally moving a little wooden mouse atop the router table. This became common in our team's production process — repurposing things in unexpected ways to solve weird problems we created for ourselves.

BUILDING THE BACKEND FOR AN INTERACTIVE SILENT FILM

Ben: Ivan spent November and December 2024 animating. Meanwhile, from Uruguay, I worked on things I felt *Éalú* would need to function as a proper game: save files, a menu, and a game manager (a persistent script commonly used to

track game state and progress). By January 2025, Ivan had 25 of 74 rooms animated, and I began integrating these animations into Unity.

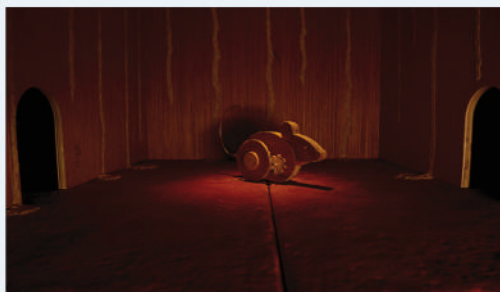
My approach in Unity was to use an overlooked built-in component; the video player. For the proof of concept, I wrote a script that would loop the mouse's idle animation. But in testing, Ivan and I discovered that while Unity was queuing the next video, the video player would go momentarily blank. This generated a split-second visible black screen which broke seamless playback. To fix this, I placed a sprite in the background, scaled it to the screen size, and set it to display the last still frame of each animation, and voilà! It filled the split-second black screen and smoothed things out!

The next step was to move the mouse from its idle position to one of the room's exits. I needed a more complex system to track where the mouse "is," and which video's currently playing, and which video plays next. Tracking a character's position is relatively simple in rendered games, where the character is an object in the rendered space that can report its position, speed, and other properties to the game manager. In *Éalú* the character doesn't exist in a rendered space; none of the objects do. I do, however, always know which mouse animation plays on game startup, which room the mouse just exited or entered, which video is playing at any given moment, and which buttons our player clicks. So given all this, my code tells the video player the correct video to sequence next. Storing and retrieving the mouse's state and player inputs made it possible to create the illusion of a continuous, dynamic animation.

Things get trickier when there are objects in a room, like puzzles, that must move asynchronously to the mouse, or that move based on player input. Ivan and I made a concession to use sprites and the Unity animator to animate these objects. Since all of the animations were captured with a single, fixed-position camera, Ivan was able to maintain consistent lighting conditions for objects I turned into sprites. He animated them in situ within the same set as the mouse, then digitally removed the rest of the scene. Finally, I composited the resulting sprites into the scenes in Unity. With a fair bit of coding

PROJECTS: Stop Motion Video Game

Screenshots from the *Éalú* video game.



and work in the Unity animator to coordinate the movement of the sprites, the end result was the illusion of asynchronous object movement, making for smooth, organic, and mechanically satisfying puzzles.

To bring everything together and create the feel of a playable silent film, Will Wood joined as our composer. Working in his studio with playtest footage in front of him, he created layered instrumentals, looping tracks for each zone of the maze to communicate their emotional tone, which I integrated into our game's backend. For the cutscenes, Will wrote short pieces specifically timed, second by second, to match the events shown. The combined effect of Ivan's and my fluid visuals and Will's music without in-game sound effects achieved our goal of emulating early silent films.

A SLOW, MANUAL PROCESS ALIGNED WITH THEME

Ivan: An unintended consequence of hand animating a game was impacting *Éalú*'s code development workflow. Whereas normally Ben might be able to reuse entire blocks of code frequently, developing our game's scripts was fairly manual and repetitive. Each room of the maze has a different number of videos, doorways, and interactables. It wasn't immediately clear

to Ben how to scale his proof of concept in Unity without re-creating and modifying his script for every room. After racking his brain, he made a hard decision to live with the technical debt incurred by scaling our proof of concept as it was. Despite shortcomings, this method seemed like the best path to reach our October 2025 launch goal. We had a bit of solidarity in that the process of coding *Éalú* for Ben became almost as manual and repetitive as my process for animating.

Given that *Éalú*'s story is rooted in my feelings about online attention-capturing algorithms, it seemed natural that our coding and animation processes begrudged overly automated, quick, or procedural methods. Extremely few games have been made this way, so there was little to no roadmap to follow. It forced Ben and me to work within tight constraints, think carefully, plan ahead, solve difficult puzzles, and devote long stretches of attention to our tasks. This more manual approach to software development was a risk for Ben. My old-school stop motion technique, lacking keyframes or any significant post processing, was for me also. With our clear scope and entire game planned out, these risks became manageable.

The experience Ben and I were creating for players mirrored our own experience crafting it, as *Éalú* encourages sustained attention,

exploration, reflection, and writing down notes. The game's pace is deliberately contemplative. We both felt that the point-and-click input system would complement the "old-school" feel of stop motion, and would allow more players who might not be familiar with complex gamepad controls to engage with the puzzles. While *Éalú* comments on algorithm-driven behavior, I hoped that the experience of playing it would inspire a contrasting feeling of something that was deeply human, imperfect, tactile, and made with love.

WHAT BROKE, WHAT SURPRISED US & WHAT WE LEARNED

Ben: Early on, Ivan and I discussed how creating a stop motion game meant that, if a room or puzzle didn't work or wasn't solvable by playtesters, or if any additions were needed, we'd have to fully reshoot and rescript the room. Doing so is laborious, as even simple rooms have five animations made from over 150 photos. I applied the "test early, test often" principle, inviting playtesters as soon as possible, and documenting their gameplay. Luckily there was never a need to redo a puzzle, but several corridors containing clues had to be reshot by Ivan, along with all of the hazard rooms to adjust them for fairness.

The most significant problem I faced was the technical debt incurred by having unique scripts for every room. While this gave me a lot of flexibility early on, managing 95 scripts quickly became very challenging, especially when a simple adjustment to the cursor, for example, needed to be repeated for every script. This is something that would have certainly stifled adding any more complexity to the game.

Players found more problems after launch, such as edge-case scaling issues impacting players using unusual desktop resolutions, and long load times affecting some players on lower-spec PCs due to inefficient processes. It's not uncommon to encounter emergent issues when your game launches, but Ivan and I both take it to heart and are still working to find solutions.

We were surprised and delighted by people's response to the interactive art we created. It's becoming clear that there may be amazing opportunities in game design to be explored within the niche genre of full motion video/stop

motion video games that we never would have dreamed of before. Also surprising was how deeply players across the world connected to the mouse, the physical world it inhabits, and the wordless story that unfolds.

ADDING OUR LINK TO A CHAIN

Ivan: While creating *Éalú*, Ben and I were deeply inspired by other artists and projects, such as Rand and Robyn Miller's work developing the game *Myst* and Lotte Reiniger's gorgeous, pioneering work in stop motion animation. I hope our game might contribute in a similar way to people's own projects.

As an expression of gratitude, I made template files for *Éalú*'s mouse puppet available to download for free in case players might like to make their own replica and learn how the puppet works. It was exciting to see them do so, with one player even emailing us a photo of a gorgeous, functional replica they made using furniture felt and copper wire.

Ben and I feel like this is, in a way, closing the loop: Physical objects and crafting translated into an interactive, digital experience, leading to players engaging in physical crafting. If players walk away pondering the topics of interaction with digital systems and the place of physical art in modern entertainment, we feel our game will have been a success. 🐱



Watch the *Éalú* gameplay trailer:
youtu.be/Z1wYp-KUxFo



Fan build: One *Éalú* player re-created the mouse puppet using free template files shared by the game creators.

TAKING PHYSICS FOR A SPIN

DEFY GRAVITY BY DESIGNING A WHEEL
THAT WILL FALL THE SLOWEST

WRITTEN AND PHOTOGRAPHED BY JOAN HORVATH AND RICH CAMERON



JOAN HORVATH and **RICH CAMERON** are the co-founders of Nonscriptum LLC (nonscriptum.com). They are the authors of many books, including *Make: Geometry*, *Make: Trigonometry*, and *Make: Calculus*.

We often think of “physics experiments” as complicated, multimillion-dollar piles of electronics. However, we can explore core physics concepts like moment of inertia and conservation of energy with a few simple components. To show you how, in this article we describe how to create a falling, spinning wheel, which is a surprisingly subtle system. We hope you will come up with a bunch of designs and see who can design the slowest-falling wheel!

MAXWELL’S WHEEL

First let’s talk about energy. Toss a ball into the air. It slows steadily until it hits a high point, then falls faster and faster. The ball at its highest point momentarily is not moving, but it *could* fall, so we say it has **potential energy**. As it starts falling and speeds up, it will get closer to the ground (less potential energy) but now, as gravity accelerates it, some of that energy turns into **kinetic energy**. Kinetic energy is the energy that something has when it is moving; a ball moving fast does more damage to something it hits than one moving slowly. Energy is not created or destroyed, so the total of our ball’s potential and kinetic energy has to stay a constant.

Let’s design something to fall more slowly than a free-falling ball, and try to predict its speed. In fact, let’s see how we can make the slowest possible descent. One way to do that is to make our falling object spin. Then it stores **rotational energy**, instead of falling at full speed. This is how a yo-yo works, but a yo-yo is a bit complicated. Let’s make one spinning, falling disk to analyze instead.

This experiment is sometimes called Maxwell’s Yo-yo or Maxwell’s Wheel (although the latter also refers to an experiment about colors). Some people think it was named after the Scottish physicist James Clerk Maxwell, but others think this is just confusion with his other experiment about colors. We will just call it a wheel for our purposes. If you search online for “Maxwell’s Wheel” you’ll find many videos, alternative analyses, and experiment ideas that you can try.

3D-PRINTED PARTS

The wheel has a few distinct parts: an inner hub it spins around, an outer part that contains the

TIME REQUIRED: 1 HOUR + PRINT TIME

DIFFICULTY: EASY

COST: A FEW DOLLARS

MATERIALS:

- **Pencils with hexagonal cross-section** like #2 or golf pencils. You could also substitute dowels and some hot glue.
- **3D-printed Maxwell’s Wheel models** as described in the article, or craft material equivalents
- **Masking tape**
- **Sewing thread**

TOOLS:

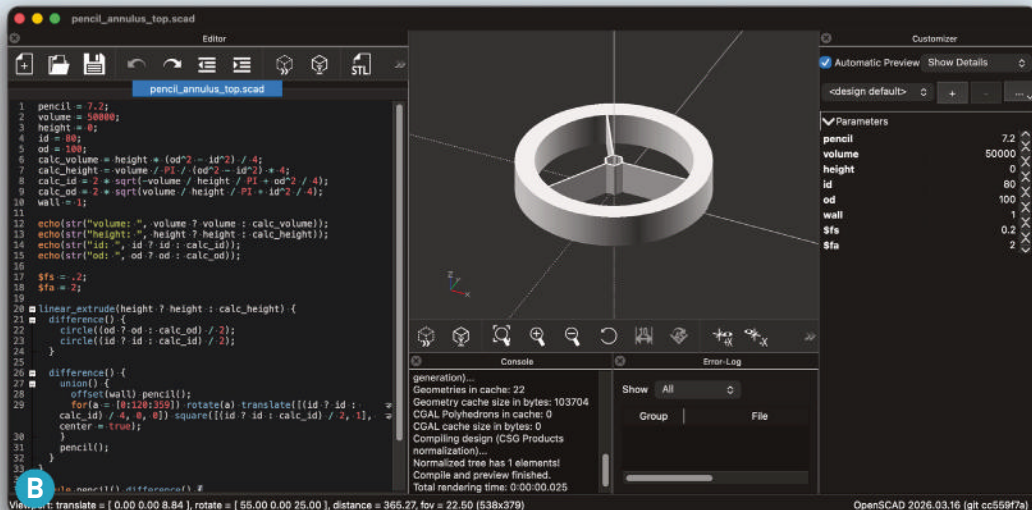
- **Computer** to download OpenSCAD file *pencil_annulus_top.scad* and 3D printable files *pencil_annulus_ring.stl* and *pencil_annulus_disc.stl*, free download from makezine.com/go/maxwell
- **3D printer (optional)** or send the 3D files out to a printing service
- **Ruler or calipers**
- **Stopwatch** or equivalent phone app



bulk of the mass, and three spokes connecting them (Figure A). We have developed a 3D printable model in the OpenSCAD language, *pencil_annulus_top.scad*, that creates a hexagonal hub designed to slip over a golf pencil, which provides a sturdy, standard axis. (A regular pencil works too, but is a bit unwieldy.) There are two basic designs we will test here, but you can try out other options as well!

If you want to learn a bit about OpenSCAD so

PROJECTS: Maxwell's Wheel



you can change the model yourself, you can find its documentation at opencsad.org, or check out our tutorial in our *Make: Geometry* book. The OpenSCAD model, and two variations that are ready to 3D print, can be found at makezine.com/go/maxwell. OpenSCAD is a **parametric** CAD program that works purely from text code, so we can supply you with a model that only requires editing a few numbers. You can see the list of parameters in this model in Figure B in the right-hand column.

To create a solid disk-shaped wheel, print the model *pencil_annulus_top.scad* with the inner diameter (**id**) parameter set to 10. (This is available as the 3D printable file *pencil_annulus_disk.stl*.) 3D print the model with close to 100% infill if possible, to minimize the unknowns in the mass distribution. Write down how much filament your 3D printer slicing program says the model will use.

To create a hoop-shaped wheel, start with the same model, but change the **id** parameter to 80, or use the printable file *pencil_annulus_ring.stl*. Again, print it nearly solid. Take a look at the projected filament usage, and tweak the infill up or down a little to get it to match the solid disk if possible. These models were designed so that they would have roughly the same mass as each other, which means the hoop is thicker than the disk in the axial direction. The center parts will be very thin for the hoop version. We recommend against filament with fibers for this version, and be sure your platform is clean!

Only one parameter needs to change between these two prints! The model has variables for volume, height, inner diameter, and outer diameter. It is coded to allow us to set any one of these values to zero to have it automatically calculated from the other three. For this purpose, only the inner diameter variable should be changed, and the height should be calculated automatically.

ASSEMBLING THE WHEELS

Take two golf pencils and slide one through the central hole in each wheel. Adjust the pencil so that it extends roughly the same distance on either side. Now find a place to suspend them; the higher the better. A door frame will work nicely, or failing that, a table. The longer the distance from this support, the easier it is to measure the time for the wheels to hit bottom.

Take two pieces of sewing thread a bit shorter than the height of your support and tie one end tightly to each side of the pencil “axle.” Put a piece of tape over the loop of thread on each side to secure it from spinning (Figures C and D). We’re using a thread on either side to keep the device symmetrical.

Now carefully measure the diameter of the pencil and divide this number by two. This is the radius that controls how fast our string plays out. When we do the actual math, we will have a couple of different radii running around, so we need to keep track. If you have calipers, they might come in handy here. Otherwise lay the

pencil on a ruler and eyeball it as best you can. We measured our golf pencil as a radius of 4mm (diameter of 8mm) but apparently a bit over 7mm is a standard diameter, perhaps measured between facets of the hexagonal cross-section. Measure the radius of the disk of the wheel as well, and the inner diameter of the hoop. If you use the defaults in the OpenSCAD file, it will be the same as for our experimental results given below.

Attach the top of each thread to your door frame or table so that the wheel hangs squarely. It is extremely important that thread lengths are equal, so that the pencil axle is level when hanging (Figure E). Ideally, it would be good to clamp the top end onto something.

Carefully measure the distance from where the string leaves the door frame or table to the outside edge of the wheel when the string is fully unwound.

DOING THE EXPERIMENT

Wind up the string around the pencil while keeping the thread taut. Note that as the thread winds over itself, the radius will increase slightly. If the thread on one side is allowed to wrap over itself more than the other, the pencil will no longer hang level.

Now, release one of the wheels to fall and use a stopwatch to time how long it takes to get to its lowest point. Repeat several times and take the average. Then repeat this for the other wheel. Write down these trials to compare them with the predictions that follow. The wheel will bounce up and down a few times until friction, drag, and other effects overcome its remaining angular momentum, but we only care about the first downward leg. It's also instructive to suspend both wheels and release them together to see their relative speeds and how much each one slows down its fall because it is being spun up.

MOMENT OF INERTIA

When we try to exert force on an object, the heavier it is, the harder it is to push around. That's *inertia*. The same is true for spinning up something, but in this case it's not just the mass, it's something called the *moment of inertia*. To figure that out, we take all the bits of mass that



PROJECTS: Maxwell's Wheel

make up the rotating object, and multiply them by the square of the distance of that bit of mass from the axis of rotation. Then, we add up all those products.

When we make something rotate, instead of applying a linear force we apply a **torque**. Just as a heavier weight requires more force to move, a higher moment of inertia requires more torque to get a desired change in rotational speed.

The moment of inertia (usually denoted by a capital *I* in equations) depends on the body's axis of rotation. If, for instance, our disk is rotating about a skewed axis, our mass distribution may become far more difficult to compute. Or if an object is made of materials of very different densities, it will have a more complex representation of its center of mass. The moment of inertia of a disk of radius *R* and mass *m* rotating about its center, for example, is

$$I = \frac{1}{2}mR^2$$

Let's say we have a soup can of mass *m*, radius *R*, and height *h*, and we spin it about an axis running through the center of the top and bottom of the can. That equation is the same as the disk (assuming we consider the can and its contents to be constant density) since a soup can is a cylinder, a sort of a fat disk.

But if instead we spun it end-over-end about a line piercing the sides of the can, it would be different:

$$I = m \left(\frac{R^2}{4} + \frac{h^2}{12} \right)$$

(This formula is from the handy table in the Wikipedia article, "List of moments of inertia.") We could of course take into account that the metal can and the soup in it were different densities and work it all out. We'd need to do some calculus to keep track of the two densities and their positions relative to the axes. In real life, the soup is a fluid, too, which complicates matters a lot as well.

TABLE. EQUATIONS FOR TIME TO FALL

	TIME TO FALL (SECONDS)
Rotating disk of mass <i>m</i> and moment of inertia <i>I</i> , about an axle of radius <i>r</i>	$\sqrt{\frac{2L}{g} \left(1 + \frac{I}{mr^2} \right)}$
Solid rotating disk of radius <i>R_o</i>	$\sqrt{\frac{2L}{g} \left(1 + \frac{\frac{1}{2}mR_o^2}{mr^2} \right)} = \sqrt{\frac{2L}{g} \left(1 + \frac{R_o^2}{2r^2} \right)}$
Rotating hoop, outer radius <i>R_o</i> and inner radius <i>R_i</i>	$\sqrt{\frac{2L}{g} \left(1 + \frac{R_o^2 + R_i^2}{2r^2} \right)}$
Freely falling, non-rotating object	$\sqrt{\frac{2L}{g}}$
Symbols used, and units: <i>g</i> is acceleration due to gravity, 9.81m/s ² <i>I</i> is the moment of inertia (kg-m ²) <i>m</i> is the mass of the wheel (kg) <i>L</i> is the length of the suspending strings (m) <i>r</i> is the radius of the pencil (m) <i>R_o</i> and <i>R_i</i> are the outer and inner diameters of a hoop (m).	

PREDICTING TIME TO FALL

So let's go back to our simple disk rotating around its center. We can use a bit of calculus and physics to figure out how long it should take for the wheel to fall if it is suspended on strings as in Figure D. The time to fall is given as the first entry in the table on the previous page. To see where this equation comes from, check out Chapter 8 of our new book, *Make: Physics*. Be careful of the units: g is in meters per second squared, so be sure all your length measurements are converted to meters. Predictions for our other two cases, putting in specific values for the moment of inertia into the general equation we just noted, are also listed in the table.

As a side note, if the wheel was just falling freely and not rotating, the equation for time to fall a distance L becomes just a function of the length of the string and the force of gravity, as shown in the last equation in the table.

OUR RESULTS

The hoop should fall slower than the disk; its time to fall will be higher. (Why? The hoop's mass is distributed further from its axis, making it harder to spin.) How much slower will depend on the relative sizes of r , R_o , and R_i . In our case, $r = 0.004\text{m}$, $R_o = 0.05\text{m}$, $R_i = 0.04\text{m}$ and $L = 1.8\text{m}$. This gives us a predicted time of 5.4 seconds for the disk and 7.0 for the hoop. Measured values were 5.3 and 6.8 respectively. Note that the solid disk is essentially the hoop with $R_i = 0$. We ignored the inertia of the pencil and the spokes holding the hoop, air resistance, and so on, not to mention the errors in measuring all around.

For these simple shapes, the mass of the body falls out of the equation completely, and, as Galileo showed 400 years ago, the speed of a non-rotating falling body is independent of its mass. (If it is rotating, though, it is not independent of its geometry.) If you let the wheel fall freely, it will bounce up again partway and oscillate (less each time) until friction and other effects eventually bring it to a stop.

OTHER OPTIONS

TOPS: We have also used the wheels as spinning tops (Figure F). We tried this at a school Maker



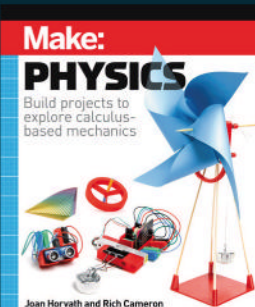
Faire and asked attendees to guess which top would spin the longest! (That one is harder to measure consistently, which is why Maxwell's Wheel works better for a physics demo.)

YO-YOS: Of course, you can always put a second wheel on the pencil and make a yo-yo! That will be more stable, but a bit less clean to talk about as a physics demo.

TRY IT!

Try experimenting with creating different wheels with different moments of inertia to see how well your predictions match their motion. To learn how to deal with more-complex shapes, look up the "parallel axis theorem." If you're a teacher, this is a great way to introduce students to the concepts of center of mass, moment of inertia, angular momentum, torque, and more!

For more background and more projects like this, check out our brand-new *Make: Physics* book, available at makershed.com/physics. 📖



Make: PHYSICS
Build projects to explore calculus-based mechanics
Joan Horvath and Rich Cameron

WANT MORE?

This article is adapted from the new book *Make: Physics*, available at bookstores and the Maker Shed, makershed.com/physics.

MEASURE THE HEIGHT OF THE OZONE LAYER

EARTH'S ATMOSPHERIC "SUNSCREEN" IS VITAL TO LIFE. FIND ITS PEAK ALTITUDE WITH THIS DIY INSTRUMENT

WRITTEN AND PHOTOGRAPHED BY FORREST MIMS III

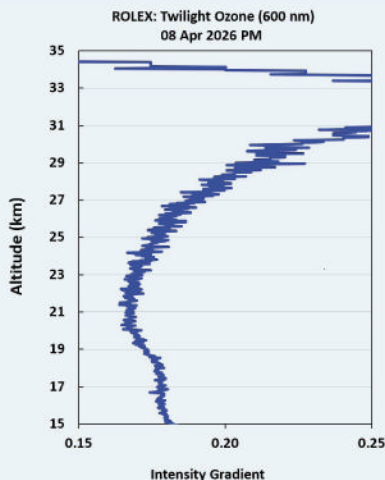
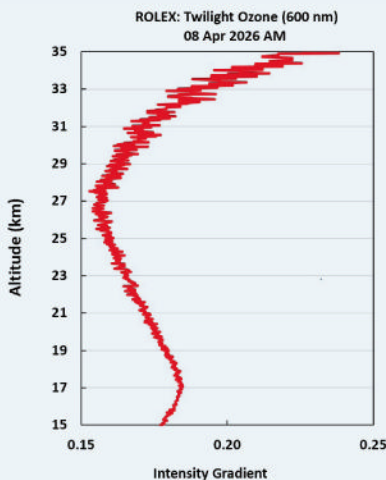
A



FORREST M. MIMS III (forrestmims.org) is an amateur scientist and Rolex Award winner whose books have sold more than 7 million copies, including *Maverick Scientist* and *Forrest Mims' Science Experiments*, both available at makershed.com. His twilight research has been sponsored by NASA and Rolex.

NASA

B



Morning and evening ozone height change during a single day.

The ozone layer envelops the entire Earth and protects us all — animals and plants — from most of the sun's dangerous ultraviolet rays.

While there is some ozone at the surface, the main ozone layer begins at the bottom of the stratosphere, just above the troposphere where we live and where weather occurs. This boundary is called the **tropopause**.

You can see where the tropopause merges into the stratosphere when a major thunderstorm is nearby. The anvil-shaped top of these storms flattens out at the tropopause.

Astronauts can see the ozone layer when the sun is just below the horizon. Figure **A** shows a 2014 photograph made by astronauts aboard the International Space Station (ISS) at sunset over Papua, New Guinea, that shows a very large thunderhead over Australia 1,500km (900 miles) away. The orange layer is the upper troposphere. The stratosphere begins at the tropopause just above the thunderhead, and the thick blue layer is the main section of the ozone layer. (For more details, search online for "ISS041-E-105277".) The lighter blue is the mesosphere.

The ISS photo suggests that ozone forms a thick, protective layer. But if all the ozone over your head were brought down to sea level, atmospheric pressure would compress it to a layer only 2.5 to 3.5 millimeters thick (0.1 to 0.14 inch). That's around the thickness of a stack of two pennies!

In the central United States, the peak thickness of the ozone layer occurs at an altitude of around 25km (15.5 miles), and it thins out at around 40km (24.85 miles). Because of aerosol interference, a twilight photometer can measure the height of the ozone layer much more accurately than the full profile.

Figure **B** shows how the peak altitude of the ozone layer can change significantly during a single day when stratospheric disturbances occur. At least that's what Grok suggested when I reported this unusual pair of plots, which were made from my field in Texas the morning and evening of the same day.

You can see various ozone profiles measured by satellites by searching online or using Grok, ChatGPT, and other AI resources.

TIME REQUIRED: A WEEKEND

DIFFICULTY: INTERMEDIATE

COST: \$80-\$350

MATERIALS:

- **Printed circuit board** \$8 each from Don Wilcher, mrdon219@gmail.com
- **Amplifier IC chip**, SMD Analog Devices ADA4530, about \$30-\$40
- **Capacitor**, 20pF — C_F in schematic diagram
- **Capacitor**, SMD, 0.01μF — C_1
- **Capacitor**, SMD, 100nF (optional) — C_2
- **LED with clear lens**, 620nm, COB package from AliExpress — LED
- **Resistor**, 5GΩ or 10GΩ (gigohms) AliExpress — R_F
- **Switch**, miniature SPST toggle — S1
- **Connector header**, 4-pin, through-hole 0.1" (2.54mm) spacing such as Würth Elektronik 61300411121, Digi-Key 732-5317-ND
- **Battery**, 9V
- **Battery connector**, 9V, with wire leads
- **Metal enclosure**, 2¼"x2¼"x5½" from Hobby Lobby
- **Bubble level**
- **Hookup wire**
- **Data logger**, 16-bit Onset UX120, with 10V DC voltage sensor cable

FOR THE FANCY BUILD:

- **Lens tubes**, 3" (2) Thorlabs SM1L30 (\$31) and SM1M30 (\$23)
- **Lens**, 150mm, mounted Thorlabs LA1433-AB-ML (\$55)
- **Threaded lens ring** included with Thorlabs lens tubes
- **Pipe insulation foam tube**, 1" inner diameter, 4" length

FOR THE MORE AFFORDABLE BUILD:

- **Fresnel lens**, credit card sized about \$3

TOOLS:

- **Soldering iron and thin solder wire**
- **Desoldering wick**
- **Drill and 1" variable drill bit** aka step bit
- **Computer with internet access and spreadsheet software** such as Excel or LibreOffice, free download at libreoffice.org
- **Disposable vinyl gloves**
- **Isopropyl alcohol**
- **Saucer**, clean
- **Masking tape**
- **Tweezers**
- **Needlenose pliers**
- **Magnifier with illumination** ideally head-mounted
- **Contact cement** such as Gorilla Clear Grip
- **Leather gloves**
- **Air duster** (optional)

NOTE: Most ozone layer plots show the peak ozone on the right side of the chart. This is reversed when plotting twilight photometer data, which indicate a decline in the twilight signal when ozone is present.

Atmospheric scientists track the ozone layer's altitude because of its role in atmospheric circulation, rainfall, and studies of ozone's recovery from losses caused by CFCs. I track its altitude for the same reasons, and to look for unexpected changes caused by unknown reasons.

Measuring the peak height of the ozone layer is the objective of this article. We will follow the footsteps of ozone pioneer F.W.P. Götz, who in 1930 made the first measurements of the height of the ozone layer over Arosa, Switzerland, with a bulky Dobson spectrophotometer pointed at the sun. I am very familiar with this instrument, for in 2016 I calibrated the world standard Dobson for NOAA during two months at Hawaii's Mauna Loa Observatory.

Extracting the height of the ozone layer from Dobson measurements is not simple, so there is now much more interest in satellite ozone data. I have long wanted to develop a much simpler ground-based method based on twilight photometry.

While the strongest absorption of ozone occurs in the ultraviolet (UV) wavelengths, the French chemist and physicist James Chappuis discovered in 1880 that a broad band of visible light peaking at 575nm (yellow) and 603nm (orange) is also absorbed by ozone. In 1954, O.R. Wulf of the Smithsonian Astrophysical Observatory found variations in the ozone column during twilight caused by this **Chappuis absorption**.

I finally succeeded in measuring the height of the ozone layer with a twilight photometer on July 20, 2016, at the Mauna Loa Observatory using a 620nm LED for a detector (detection peak around 600nm) and an op-amp with a huge feedback resistor of 20 gigohms (GΩ). The peak ozone layer height from the photometer was 25.3km (15.7 miles) while a balloon-launched ozonometer launched from Hilo measured the peak height at 25.9km (16.1 miles), a difference of only 0.6km (0.4 mile) or about 2.5%.

TWILIGHT PHOTOMETRY

It is rather astonishing that a handheld instrument can accurately measure the height of the tropopause (10–15km or 6.2–9.3 miles), aerosol layers (5–25km or 3.1–15.5 miles), the ozone layer (25–35km or 15.5–21.8 miles), and even meteor smoke in the thermosphere (80–110km or 49.7–68.4 miles).

You can acquire these results during twilight by pointing straight up at the sky a filtered photodiode or LED connected to a very high-gain amplifier. This instrument is a **twilight photometer**, and construction details for one of my earliest were published in *Make*: Volume 44 (makezine.com/projects/twilight-photometer) and also in my book *Make: Forrest Mims' Science Experiments*.

Here we will cover how twilight photometry can be achieved with a suitable LED mounted at the focus of a small telescope. The telescope is pointed straight up for an hour or more before sunrise, or after sunset. The LED will observe the light from the edge of Earth's shadow as it rises or falls in altitude during twilight. The LED's signal is amplified, stored in a data logger, and later processed in a spreadsheet program such as Excel.

My twilight photometry research described in *Make*: led to an assignment from NASA's Dr. Dong Wu to develop twilight photometers to measure the altitude of aerosols from the historic eruption of the Hunga Tonga undersea volcano in 2022. For that project, I retained Hagerup Technical Services to construct five twilight photometers using LEDs as photodiodes.

While conducting Hunga Tonga aerosol measurements, I noticed that the NASA photometers found the altitude of the tropopause by detecting a subtle change in aerosols that occurs there. Earlier researchers mentioned this possibility, but never pursued it. Our many twilight measurements were within a few percent of the tropopause measured by weather balloons launched by the National Weather Service. This finding was so significant that Dong and I wrote a formal paper in 2024, "Tropopause Height Inferred from Twilight Photometry" in *Bulletin of the American Meteorological Society* (doi.org/10.1175/BAMS-D-24-0054.1).

The tropopause is the boundary between the troposphere, where weather occurs, and the very stable stratosphere, where the ozone layer occurs. It is typically 9–12km (5.6–7.5 miles) high over the U.S. When possible, aircraft pilots prefer to fly above the tropopause where the air is much more stable.

ULTRA-SENSITIVE OZONE LAYER TWILIGHT PHOTOMETER

My first twilight photometers used conventional, low-noise op-amps with ultra-high-resistance feedback resistors.

The NASA-inspired photometers used a 1" telescope and an Analog Devices ADA4530, a relatively expensive surface-mount (SMD) op-amp that can amplify the photocurrent from an LED a trillion times. This ultra-high amplification provides less noise than my previous photometers.

The NASA twilight project led to a grant from Rolex to develop a much simpler photometer with even less noise than the NASA-sponsored units. While the NASA instruments worked well, I designed a much simpler circuit that used only an ADA4530, a 5GΩ or 10GΩ feedback resistor, and a small feedback capacitor (~10pF–20pF).

For the first time since I began twilight research in 2013, the new ultra-simple design sponsored by Rolex displayed a sharp negative spike at the tropopause rather than the slight dimple displayed by the NASA photometers. This spike was caused by a sharp drop in aerosols that clearly indicates the tropopause.

BUILDING AN ADA4530 TWILIGHT PHOTOMETER

There are various ways to assemble a twilight photometer using the ADA4530 chip. Some are much less costly than the method described here. For example, you can use a \$3 Fresnel lens instead of the expensive Thorlabs telescope I used.

Either way, the ADA4530 chip (\$30–\$40) and an LED are installed on a tiny 7/8"-diameter printed circuit board that fits inside a telescope tube. My friend Don Wilcher designed the board and arranged for its fabrication.

1. CLEAN

Cleanliness and a dust-free room are essential when assembling an ultra-high-gain twilight photometer. While holding the circuit board by its edges with clean hands, thoroughly wipe both sides with a clean paper towel soaked in isopropyl alcohol. Allow the alcohol to stay on the board for a few minutes. Then hold the board securely by its edges and blow away the alcohol with a blast from a canned air duster.

2. ASSEMBLE CIRCUIT

Your best friends here are a hands-free method of holding the circuit board, along with disposable vinyl gloves and a head-mounted magnifier with an LED illuminator. Begin assembly by placing the dry board atop a clean saucer with the copper pads facing up. Keep it in place with a bit of masking tape.

2A. CAPACITOR

Next, solder C1 to the board. Be sure to hold the tiny capacitor with tweezers and do not touch it or the surface of the board with your bare fingers. Apply a thin layer of solder to one of the two pads for C1. Then carefully place the two ends of C1 over its two pads and secure it in place with tweezers or masking tape. Carefully touch the soldering iron to the junction of the chip and the solder-covered pad. The capacitor should remain in place. Touch a solder wire to the junction of the second pad and the circuit board. The solder should flow around this end of C1 and secure it to the board.

For more tips on surface-mount soldering, see the expanded version of this article at makezine.com/go/ozone-photometer.

2B. AMPLIFIER CHIP

The gain of the ADA4530 is so high that the chip is extremely sensitive to anything touching pin 8, the input pin to which the signal from the LED used as a photodiode will be connected. Therefore, pin 8 must be very carefully bent, from straight down to straight away from the chip, before its remaining seven pins are soldered to the board.

Bending pin 8 requires considerable care to avoid dropping the expensive chip, which might bounce off the paper towel and disappear on

PROJECTS: Amateur Scientist

the floor. My approach is to hold the ADA4530 with the narrow jaws of clean needlenose pliers and use clean SMD tweezers to carefully bend pin 8 outward so it is perpendicular to the chip. (Be sure to wipe the pliers and tweezers with isopropyl alcohol before using them.) I have used this method for a dozen or more ADA4530 SMD chips, and none were dropped. If you have any spare SMD ICs, practice this procedure before doing so with the expensive ADA4530.

Set the ADA4530 on a clean paper towel. On the circuit board, carefully place a thin layer of solder over the pads for pins 1 and 5 of the ADA4530. Remove excess solder with solder wick. While wearing disposable vinyl gloves, secure the chip to the board with a bit of masking tape across pins 3, 4, 5, and 6. Then very carefully touch your soldering iron to where pin 1 of the IC touches its solder-coated pad. If the ADA4530 is properly aligned, carefully remove the tape and solder pin 5 to the board. Complete the installation of the ADA4530 by touching the remaining pins with the iron and solder wire. Use your magnifier to be sure all seven pins are properly soldered.

2C. MINI CONNECTOR

Next, insert the four pins of a 4-conductor mini connector socket into their holes on the top side of the board and then solder them in place on the back side.

2D. LED

Cut a square of vinyl tape or Velcro-style hook-and-loop tape and apply it to the back side of the board where the LED will be installed. This insulates the LED from the board. Be sure to leave the holes through the board open.

A 620nm red LED is soldered to the back side of the board. I have used both wire-lead and surface-mounted LEDs with extended, flat terminals, the latter of which I prefer. The positive pin, marked with a "+" sign, is soldered between the two center pins of the mini connector on the back side of the board.

While still wearing vinyl gloves, add solder between the two center pins of the connector. Then press the LED's anode terminal against the two connector pins and heat with your soldering



Lower side of circuit board showing the LED. Note that the LED anode is soldered to the junction of two center tabs from the socket on the front side of the board.

iron until the terminal is melted into the solder between them.

Carefully remove the insulation from both ends of a 1" length of thin hookup wire and solder one end to the LED's cathode terminal. (Bend the terminal slightly upward if it is touching the board.) Insert the other end of the wire through the pass-through hole in the board. It will be connected later. Figure C shows the back side of the board with the LED soldered in place.

2E. FEEDBACK RESISTOR AND CAPACITOR

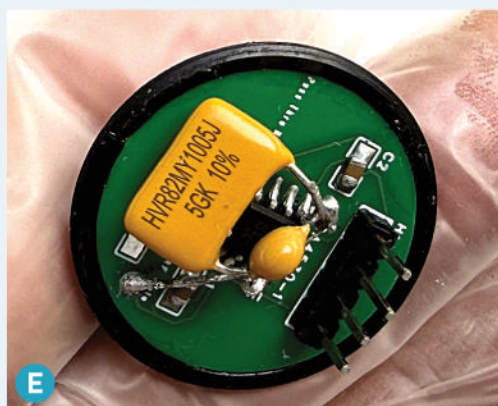
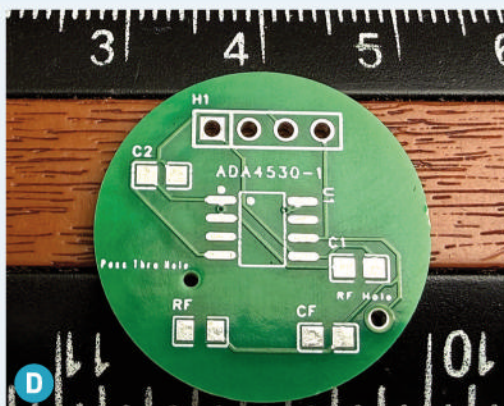
It is essential to wear vinyl gloves for the next step to avoid touching R_F , a 5G Ω or 10G Ω resistor, and C_F with bare fingers.

First, carefully solder the leads of C_F , a 10pF or 20pF capacitor, across the leads of R_F . The capacitor should be just below the resistor but not touching it. Clip off C_F 's excess leads.

Soak the combined $R_F + C_F$ for several minutes in a clean water bottle cap filled with isopropyl alcohol to remove all impurities. Agitate R_F and C_F within the alcohol before removing them. Then hold R_F and C_F with clean tweezers and blow the alcohol away with a duster.

Very carefully insert one lead from R_F through the hole between the pads for C_1 and C_F and solder the lead in place.

Bend the second lead from $R_F + C_F$ across the board and solder it to the thin wire from the LED that you inserted from the back side. The board is completed by carefully soldering a short length of insulated wrapping wire between this junction



Top side of circuit board, before and after assembly. The C2 capacitor (100nF) is used only when the circuit is powered by two 9V batteries.

and the unconnected pin 8 of the ADA4530.

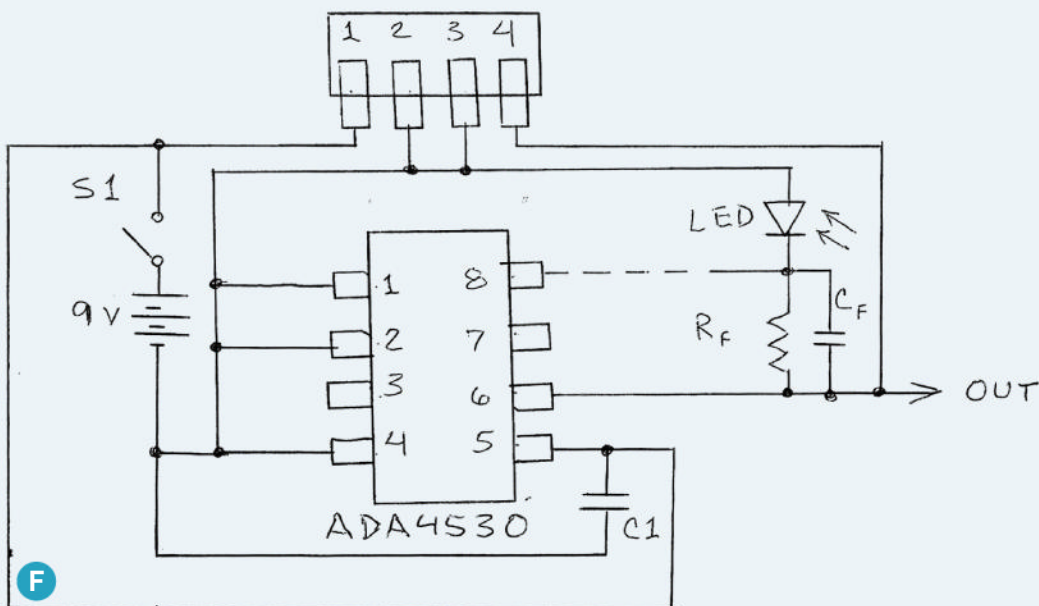
Figures **D** and **E** shows the board's top, bare and assembled. The large orange component is R_F , a 50k feedback resistor (use 100k for more sensitivity). The round object below it is the feedback capacitor C_F soldered to the leads of R_F . These components and the board itself should be touched only when you are wearing disposable vinyl gloves.

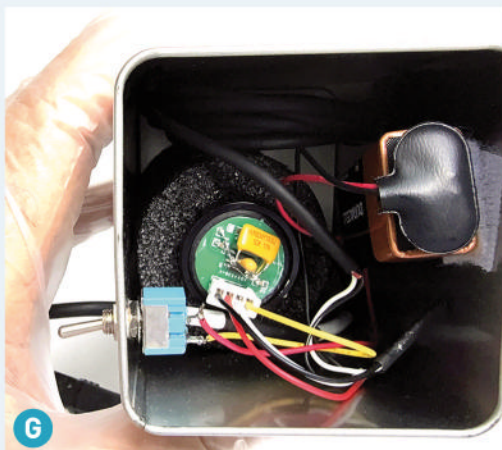
The circuit diagram in Figure **F** shows how the various connections are made between the circuit board, 4-pin plug and socket, the power switch, the 9V battery, and the Onset 16-bit data logger. After the external connections have been

made, dip the entire assembled board into a small container filled with isopropyl alcohol and gently shake the board for 30 seconds or so. This will remove dust and other contaminants that will greatly reduce the circuit's sensitivity. Remove the board and spray away the alcohol with a burst from a duster, and install the board into the end of the lens tube.

3. ENCLOSURE AND LENS

For best results, the photometer's LED should look at the twilight glow through a magnifying lens with a narrow field of view. While you can use an inexpensive plastic Fresnel lens, I used a high-





G Circuit board installed in lens tube and connected to on-off switch, 9V battery, and data logger cable.



H Completed twilight photometer.

quality glass lens and lens tubes from Thorlabs identical to those in the NASA photometers (see Materials list). These provide stability, but they can be replaced by an inexpensive Fresnel lens about the size of a credit card, cemented 1 focal length away from the LED.

Thorlabs sells a wide variety of threaded tubes for their lenses. These tubes come with internal threaded rings. The rings that came inside the tubes I ordered fit perfectly around the $\frac{7}{8}$ " circuit board designed by Don Wilcher. Inserting the assembled board into a threaded ring permits the focus to be adjusted, and also allows the circuit to be removed for troubleshooting or for changing the LED.

Select a ring that fits tightly around the circuit board. While wearing disposable vinyl gloves, carefully cement the board to the inside of the ring with a very thin line of cement. I used Gorilla Clear Grip. Make sure no cement touches the threads, for that will prevent the ringed board from being inserted into a lens tube.

I assembled my photometer inside a $2\frac{3}{4}$ " $\times$ $2\frac{3}{4}$ " $\times$ $5\frac{1}{2}$ " tin enclosure from Hobby Lobby. I drilled a 1" hole through the center of the enclosure's bottom using a step drill. This is best done by inserting a 4" scrap of 3 $\times$ 3 lumber into the enclosure. Hold the enclosure straight up with the wood roughly centered inside and resting on a flat surface. Begin carefully drilling through the center of the enclosure's bottom until the hole is 1" across. Wear leather gloves to avoid scratching

your fingers.

After the hole is carefully smoothed, insert the threaded end of a Thorlabs lens tube into the outside of the hole and screw it into a second lens tube inside the enclosure. Then push a 4" section of hollow black plastic pipe insulating foam over the internal lens tube. This provides a firmly centered mount for the circular circuit board installed inside a threaded ring.

Next, drill two $\frac{1}{8}$ " holes near the base of the enclosure, one for the power switch and one for the data logger cable. The wires from the 4-conductor connector are then connected as shown in Figure F. Coil the input cable for the data logger and insert it between the foam cylinder and the enclosure wall as shown in Figure **G**. The 9V battery can be mounted to the wall with 1" squares of self-stick velcro tape.

While wearing vinyl gloves, carefully screw the assembled circuit board into the end of the 3"-long tube that mates with the end of the interior 3" tube.

It is extremely important to avoid routing any of the external wires over the circuit board. Besides contaminating the board, they might press R_F and C_F onto the ADA4530. Therefore, all external wires must be placed around, and never over, the exposed circuit board.

Finally, install the Thorlabs lens over the end of the external tube. First, blow away dust from both sides of the lens. Use a Thorlabs lens cap or a small plastic bag to protect the lens when the

photometer is not in use. Figure **H** shows the assembled twilight photometer before an evening twilight session.

**YOU'RE IN THE OZONE ZONE
USING YOUR OZONE PHOTOMETER**

The completed photometer should be placed on a flat surface well away from artificial lights. I place a plastic level across the lenses of my photometers and use plastic furniture levels to make sure they are perfectly level before taking twilight measurements.

Various websites provide the exact time for sunset and sunrise at your location. I set up my instruments and switch them on around 10 minutes before sunset and an hour before sunrise. At my location (29.6 degrees North), an observation time of 1 hour will provide data from the ground to around 150km (93 miles). While a clear sky is ideal, data can often be collected through thin clouds.

caused by aerosols in the upper atmosphere from African dust, forest fire smoke, and the aerosols around 20km known as the Junge layer. (For those aerosols, near-infrared LEDs work best.)

The peak height of the ozone layer varies over time. At my latitude of 29.6 degrees, the peak can range from 20–30km. Figure **I** shows three typical plots during cloud-free twilights with an average peak of 27km. Fluctuations in the traces are mainly caused by aerosols, which is why I am experimenting with simultaneous measurements at 885nm, where ozone absorption is very low and aerosol effects can be problematic.

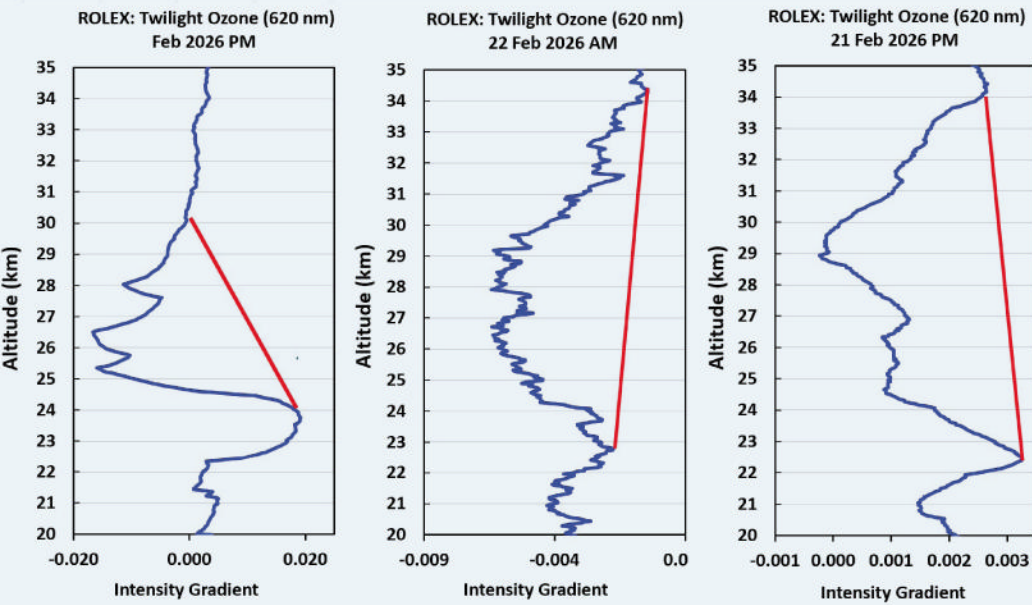
The average peak of 11 of my twilight ozone measurements made while preparing this article was 25.13km — almost equal to the NASA average over my site of 25km. 🌍



More ozone science:
epa.gov/ozone-layer-protection

PROCESSING THE DATA

My previous twilight photometry article in *Make:* provides full details on how to interpret the instrument's output during twilight. Back then my major interest was finding bulges in the data plot



Three ozone layer peaks measured by the twilight photometer from Mims' Texas field.

TRICK & TREAT BOX

SHOCK YOUR VISITORS WITH
A SPRING-LOADED SURPRISE!

WRITTEN AND PHOTOGRAPHED BY BIZZARO



BIZZARO is a professional magician from Las Vegas turned escape room and interactive experience creator. Sometimes he eats Doritos, sometimes they eat him.

TIME REQUIRED: 1 DAY

DIFFICULTY: INTERMEDIATE

COST: \$50-\$60

MATERIALS:

- Electric magnetic lock, 130lb
- Rechargeable battery pack, 12V
- Reed switch with NC (normally closed) connection
- Spring snakes, jellybean can type (4)
- ABS pipe, 2" diameter, 24" or more
- Cool box with a lightweight lid If your box has any hardware to keep it closed or locked, remove that. You won't be needing it.
- Thin metal rods, 1/8" diameter (2) about as long as your box
- Electrical wire, 22AWG
- Wire connectors (3) Wago, wire nuts, etc.
- Pigtail connector
- Square wood dowels (5)
- Wood, 2x4, 6" or longer
- Wood screws, 1" (4)
- Foamcore, black
- Magnet

TOOLS:

- Long drill bit, 3/16"
- Wire strippers
- Drill
- Ruler
- Pencil
- Hot glue
- Hand saw
- Cutting mat
- Craft knife X-Acto blade, carpet knife, etc.



MATERIALS



With Halloween just around the corner, what better way to celebrate than combining some simple tech with a good old-fashioned scare?

Pass a magnet over a hidden spot on the box and — surprise! — the lid snaps open and four spring-powered snakes fly out at your startled guest. This build takes some basic tech I use in a lot of my escape room builds and lets you add some interactive chicanery to your skill set.

1. START WITH THE TOP

If your lid has depth to it like mine, measure the length and width of the inside of the lid. If your lid is flat with no sides, you can skip ahead to step 2.

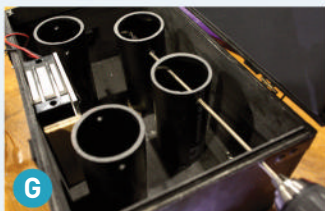
Cut the black foamcore board to match the

inside dimension of the lid. This board will need support, so put your wooden square dowel into the lid and mark where the edge is (Figure A).

Cut the square dowel to match the inside depth of the lid, minus 3/8" for the foamcore board. You will need four pieces, one for each corner. For the middle back, I used a random wood scrap I had but you can use another dowel. I used hot glue to attach them into the lid (Figure B).

2. LOCK IT DOWN

You are now going to attach the magnetic lock. These are usually composed of three parts: the strike plate (the big silver chunk of metal), the mounting bracket, and magnetic base. Usually



the base and mounting plate are attached and have to be separated (Figure C) by way of an included Allen wrench.

Hold the lock against the inside of the box, lining it up flush with the edge of the box, and measure the distance from the bottom of the box to the back of the mounting bracket. Using this measurement, cut a piece of 2x4. Remove the magnetic base from the mounting bracket and screw the bracket into the top of the 2x4, lining it up with the edge of the block of wood. Reattach the magnetic base and screw the wood block to the box from the front.

If the wood of your box is thick enough, you could skip the 2x4 entirely and just screw or bolt the mounting bracket to the wall of the box itself, but the box I got was too thin to do that and using the 2x4 gives it a lot of strength. 2x4s are also the perfect size to mount these kinds of locks.

NOTE: If your lid is flat, you need to allow room for the strike plate to line up with the base, so don't mount the base flush to the top edge of the box.

3. BACK TO THE TOP

Now you need to line up the strike plate to the magnetic base. Make pencil marks on the outside of the box that line up with the edges of the base (Figure D). Close the box and transfer those marks to the outside of the lid.

You are now going to do the same thing you did with the base. Hold the strike plate against the inside of the lid, making sure it's flush to the

edge. Measure from the bottom of the plate to the inside of the lid and cut a piece of 2x4 to that distance. Screw the piece of wood into the lid from the outside.

Now you'll line up the strike plate to your pencil marks on the box and screw it down. But first, take note: Included with almost all maglocks is a clear rubber washer (Figure E). This piece is very important. It's what makes the lock work reliably. The rubber washer goes between the strike plate and the wood. It gives the plate flexibility to shift around and seat itself properly for a secure connection. *Do not* skip this part!

To mount the strike plate I had, I needed a washer so my screw head didn't go through the recessed hole. Yours might not. Don't tighten it too much, it needs a little bit of wiggle for the rubber washer to do its job.

Finally, cut a hole in the foamcore board to fit around the strike plate. Make it slightly bigger than the plate itself. Put some hot glue on the tops of the wood dowel supports and press the foamcore firmly in place.

4. INNER TUBIN'

Stand the ABS pipe in the bottom of the box and mark its height, flush with the box edge (Figure F). I used ABS because it is already black and tends to have a thicker wall for stability. Cut four of these tubes to the same length.

Glue the four tubes into the box in whatever configuration suits your needs. I chose a staggered layout, to leave room for an object in the middle and to disperse the spring snakes'

force across the lid. I used, you guessed it, hot glue for this because it works surprisingly well with the ABS and wood. You could use epoxy but the hot glue does its job.

Drill into the box from the side and through the tubes with the long $\frac{3}{16}$ " bit, about 1" below their top edges (Figure **G**). This creates a channel for the $\frac{1}{8}$ " metal rods to slide through. (If you don't have a long bit you could pre-drill these holes in the tubes before gluing, but lining them up might be a challenge.)

5. TIME TO WIRE

For this application I am using single inline Wago wire connectors, aka Lever Nuts.

You will also need a magnetic reed switch but they're not all the same. I used the kind found on doors, as they have both NO and NC connections (Figure **H**). What you want is the NC (normally closed) port. That means the switch will supply constant power to the lock until a magnet releases it. Attach the reed switch anywhere to an inside wall of the box. I chose the side.

The wiring for this is pretty simple (Figure **I**). Once you get everything connected, hide the wires and battery in the bottom of the box. If this is going to be a permanent prop, you can wire it up to wall power using a 12V adapter power plug.

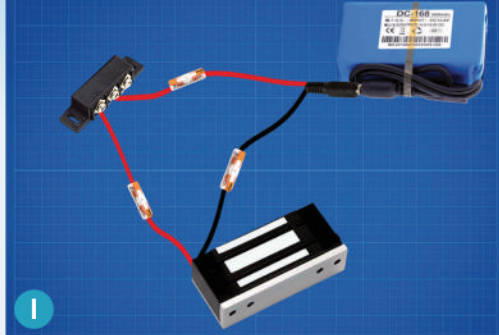
6. WHY'D IT HAVE TO BE SNAKES

Find a friend who likes jellybeans and have them open the can you bought (Figure **J**). After they get done being mad at you, take the snakes that shot out and stuff them into the black tubes.

Start on the right side and run a $\frac{1}{8}$ " metal rod through the side of the box and through the holes in the ABS pipe. This locks the snake in place. Shove the metal rod the rest of the way through the left tube, locking both snakes in place. Repeat this for the other two tubes (Figure **K**). You'll remove the rods once the lid is locked.

7. THE FUN PART

Now it's time to test it! Close the lid, making sure it locks in place. If it doesn't, check your wiring, especially the reed switch, and make sure the battery is on. If those are fine, make sure the strike plate isn't too tight and that it lines up to the base. After the lid is secured shut, place a



magnet on the outside where the reed switch is to make sure the box unlocks.

If everything is in working order, pull out the metal rods to set the box. Touch the magnet to the box and *watch out!* If everything has gone right, the lid will fly open and four spring snakes will eject from the box.

One piece of advice: Secure the box to whatever surface it's on. You can screw or tape it down.

SURPRISE SURPRISE!

There are lots of ways to use this box! You can use it as a gift box and create a scavenger hunt to have someone find a trinket to open it up. Or wire up a button on the outside of the box and fill the inside with candy for trick-or-treaters. You could even wire it up to an RF remote to trigger it when someone walks by. The choice is up to you!

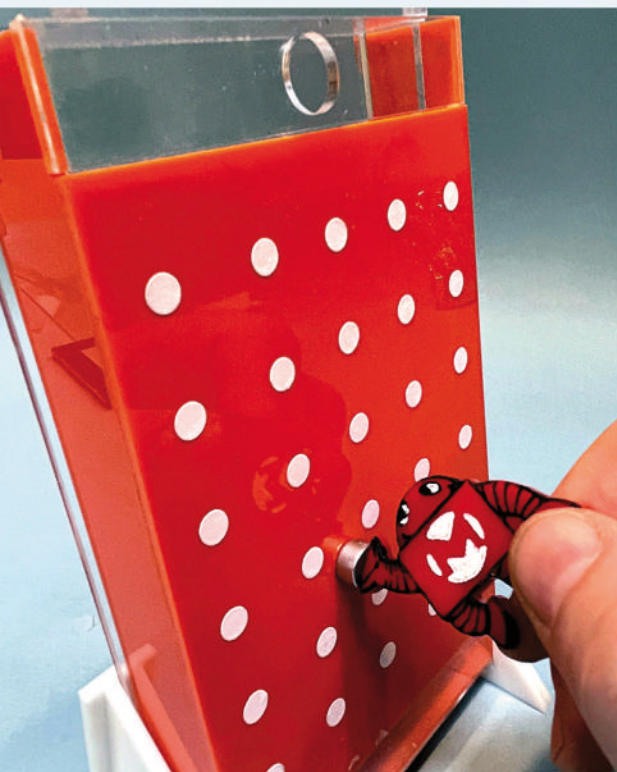
You can cover up the wires and battery in any way you see fit: paper, fabric, candy, a false bottom, etc. It really depends on your use case.

If you make your own version of this, head over to www.testsubjects.com and let us know! We would love to see it. 🍪

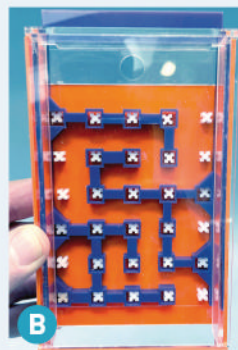
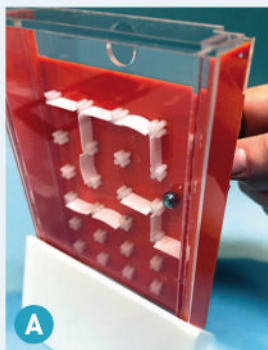
MAGNETIC MYSTERY MAZE

SOLVE THE MYSTERIOUS UNSEEN MAZE USING MAKEY'S MAGNET. GET THE BALL OUT THE TOP TO WIN!

WRITTEN AND PHOTOGRAPHED BY BOB KNETZGER



BOB KNETZGER is a designer/inventor/musician whose award-winning toys have been featured on *The Tonight Show*, *Nightline*, and *Good Morning America*. He is the author of *Make: Fun!*, available at bookstores and at makershed.com.



This game has a secret: hidden in back are movable barriers that form a maze path. Using Makey's mighty magnet, move the steel ball up through the maze. If you hit an invisible barrier, the ball falls back down to the bottom. Start over and try again! With a good memory — and a little luck — solve the hidden maze and get the ball all the way up to the top!

This game is reminiscent of a 1960s tabletop game by Schaper Toys (best known for "Cootie"!) called "The Puzzling Pyramid." This new version adds the fun of watching the player's ball from the back as they attempt (and fail!) to solve the maze (Figure A). Also added is a one-player mode with drop-in instant maze templates (Figure B).

MAKE!

1. CUT THE PARTS

Go online to makezine.com/go/mag-maze and download the SVG cutting files for your laser cutter (Figure C). You could fabricate the parts by hand instead, but making all the notched pegs would be tricky.

Cut the front panel parts from thin $\frac{1}{8}$ " colored acrylic. A darker color works best to conceal the maze on the other side. Cut the outlines as through-cuts, but only etch the cross-shaped features (those indicate where to glue the pegs).

NOTE: The small notches on the side pieces are sized to the thickness of the clear acrylic for a flush surface. Adjust this dimension to match your clear material's thickness.

- Cut the back panel and other clear parts from $\frac{1}{8}$ " clear acrylic.
- Cut the slotted pegs from $\frac{1}{4}$ "-thick acrylic.
- Cut the Makey figure from $\frac{1}{4}$ " acrylic. Cut the outline, and deeply etch the drawing of Makey.

2. MAKE MAGNETIC MAKEY

Decorate the Makey robot's details with acrylic paint: white for the eyes and M logo, black for the other details. Paint the engraved area and wipe off the excess from the top surface.

Then super glue the magnet to Makey's hand (Figure D).

TIME REQUIRED: 4 HOURS

DIFFICULTY: EASY TO INTERMEDIATE

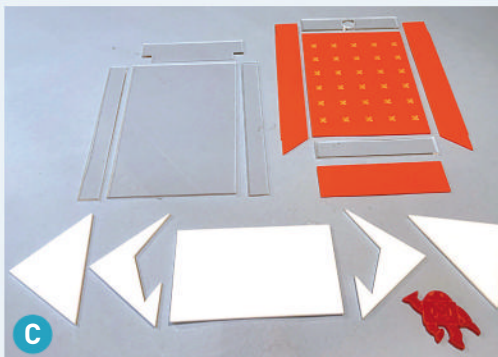
COST: \$15-\$20

MATERIALS:

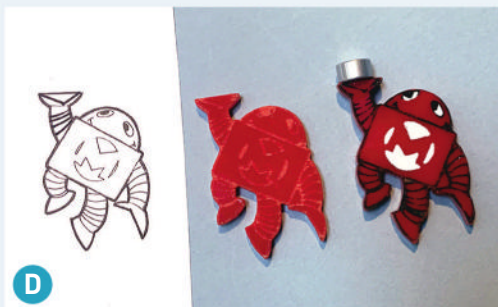
- Acrylic plastic sheet in $\frac{1}{4}$ " and $\frac{1}{8}$ " thicknesses, and various colors including clear
- Polypropylene lid like from a yogurt container
- Neodymium disc magnet, $\frac{3}{8}$ " diameter $\times$ $\frac{3}{16}$ " thick
- Steel ball, $\frac{1}{4}$ " diameter
- Acrylic solvent
- Cyanoacrylate (CA) glue aka super glue
- Acrylic paint I used white and black.

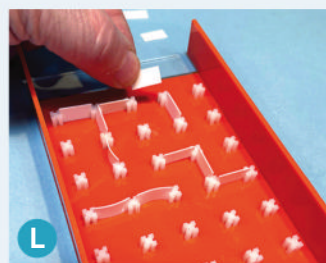
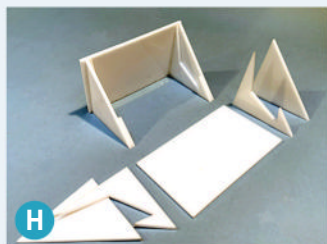
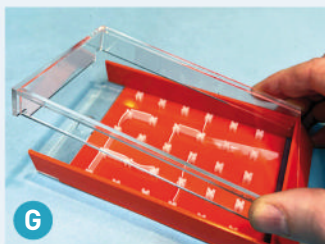
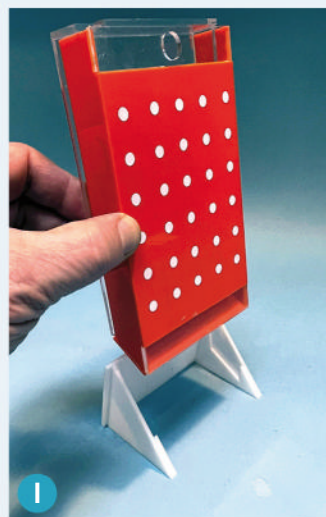
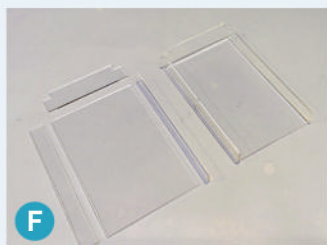
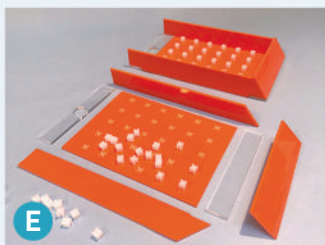
TOOLS:

- Laser cutter
- Model paint brush
- China marker aka grease pencil



TIP: I used the built-in camera of my Glowforge laser to automatically create the cutting and etching paths. This is a really fun and super-quick way to make parts that don't need critical dimensions. I just place a drawing of the part under the Glowforge's camera and it does the rest. If your printer doesn't have this feature, use the SVG cutting file online.





3. ASSEMBLE MAZE BOX

To assemble the maze box, first bond all the pegs to the back of the front panel, using the etched crosses for position (Figure E). Then bond the sides onto the back. Add the diagonal bottom panel and lastly, bond the clear panels in the notches. Be sure to glue the clear panel with the ball hole on the end opposite the diagonal panel as shown. Lastly, add dots to the outside of the box to show the maze's grid. I made white dots from peel-and-stick labels with a paper punch.

To assemble the clear back, bond the two sides to the back panel. Note that they are set in from the edges so that they will fit just inside the colored front panel (Figures F and G). Bond the T-shaped panel to the top end.

Bond together the parts to make the base. The notched shapes are laminated to the triangles to make left- and right-hand sides that will cradle the maze box. Use the finished maze box to check fit and spacing, then bond the base sides to the base back for a fit that cradles the maze box (Figures H and I).

4. MAKE MAZE BARRIERS

Cut out the flat center part of a polypropylene lid, then cut it into strips $11/16$ " wide that fit snugly between the pegs. Cut those strips into $5/16$ "-high pieces to make the movable maze barriers (Figures J and K).

PLAY!

One player creates a maze. Place the barrier strips in various positions using the notches in the pegs (Figure L). Make sure there is at least one open and continuous path from the bottom to the top of the maze!

Once your maze design is complete, replace the back and insert the maze box into the base — don't let the other player see your design! Drop the ball into the hole.

To play, the other player uses the Makey magnet to drag the ball up and around the grid of dots. Start at the bottom (Figure M) and slide Makey's magnet up, down, left, and right (Figure N). If they try to cross a hidden barrier, the ball falls back down — *klunk!* Try again and remember



to *not* go the same way again!

Eventually, they'll solve maze and get the ball to the top and out the hole (Figures **O** and **P**). Success!

You'll have the fun of watching from behind as the other player tries to solve the maze, with the ball sliding along (Figure **Q**) — or falling down!

PLAY VARIATIONS

- **Compete:** Keep track of the number of klunks. Who can solve the maze in the fewest tries? Or try solving a maze in the shortest time — who is the quickest?
- **Skill levels:** Agree on how many barrier pieces to use in building the mazes. Fewer pieces usually means easier mazes!
- **Memory aids:** Too hard to remember where the barriers are? Use a china marker to draw a line for each maze barrier you find (Figure **R**). Whew — that's better! (Carefully wipe off the markings between games.)

ONE-PLAYER VERSION

Download and cut out the completed maze template using ¼"-thick acrylic (Figure **S**). Instead of building a maze design from barrier parts, just place the template over the pegs (Figure **T**). Don't peek! You can place it without looking, as it fits right over all the pegs at once. The handle bar will stick out the top.

Put on the clear back, and place the game into the base (without looking behind). Now you're ready to try the one-player challenge — and it's a tricky maze (Figure **U**)!

For a fresh challenge, flip the template over for a new (mirror image) maze.

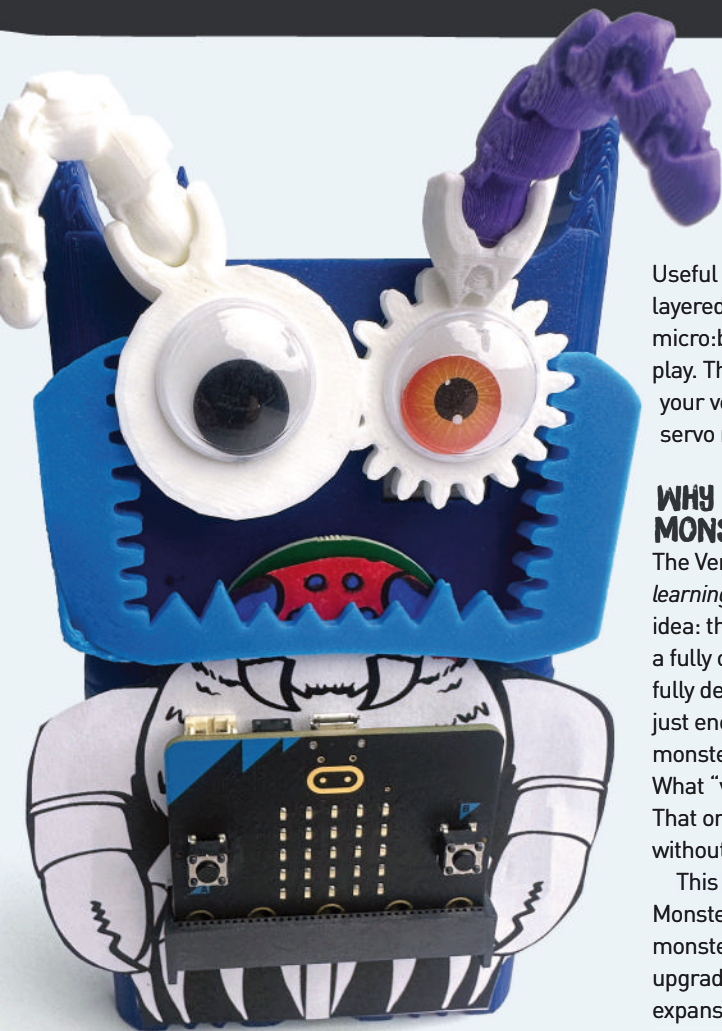
NEW MAZE TEMPLATES

You can also create your own solo play maze templates! Use a vector drawing program to modify this template to make a new maze path variation — or even create your own all-new mazes from scratch. 🌀

MY MONSTER AND ME

EXPLORE THE BBC MICRO:BIT WITH A FRIENDLY KIT THAT GROWS WITH YOU

WRITTEN AND PHOTOGRAPHED BY DIEGO FONSTAD



Every issue of *Make:* includes at least one project built around a microcontroller, but knowing where to even begin your own project is often the biggest barrier of all.

In this article we introduce the Very Useful Monster — an open source series of fun, layered projects designed to make exploring the micro:bit feel less like homework and more like play. The framework grows with you, from writing your very first program to wiring up sensors and servo motors that bring your monster to life.

WHY BUILD A VERY USEFUL MONSTER?

The Very Useful Monster is a *project-based learning curriculum* built around a key pedagogical idea: the *throughline*. Rather than giving learners a fully open-ended prompt (overwhelming) or a fully defined one (boring), a throughline provides just enough focus. You're not just building a monster — you're building a very useful monster. What "very useful" means is entirely up to you. That one constraint is enough to get started without boxing anyone in.

This project uses the Make: Very Useful Monster Ralfe kit which includes a 3D-printed monster body, pop-out eyes designed for servo upgrades, and Lego-compatible pegs for easy expansion. The 3D printing files are available to print yourself at makershed.com/ralfe.

1. GIVE YOUR MONSTER A HEART

Most tutorials start with "Hello World." We're skipping that. Our first program gives your monster a heartbeat — and teaches you how to load code onto the micro:bit along the way.



The Very Useful Monster curriculum was developed by **DIEGO FONSTAD** and educators at Imagination Supply Co. (lectrify.it).

ASSEMBLE THE MONSTER

Snap the Lego pegs into the body (two per side) to create mounting points for the MakeyBit.

Install batteries in correct polarity: positive–negative–positive–negative. Flip the on/off switch — you should see a green indicator light. If not, re-seat the batteries or roll them in the contacts to improve connection.

Slide the micro:bit firmly into the MakeyBit connector. Leave the pop-out eyes in place for now.

WRITE YOUR FIRST PROGRAM

The micro:bit can be programmed with block-based code, Python, or JavaScript through the MakeCode editor (makecode.microbit.org). Connect the micro:bit to your computer via USB and open MakeCode. You'll see an emulator on the left, block categories in the middle, and your workspace on the right.

- From the Basic category, drag a **forever** block into your workspace. This code block runs your code on a continuous loop — perfect for a beating heart.
- Inside it, place a **show LEDs** block. Click the grid to draw a heart shape (Figure A).
- Click Download. The first time, MakeCode will ask you to pair your micro:bit — follow the prompts. Once downloaded, your monster's heart begins to glow using the built-in LEDs (Figure B). It's alive!

2. TRY OUT THE ONBOARD SENSORS

The micro:bit v2 packs a surprising amount of hardware — and none of it requires extra wiring (Figure C on the following page). On the front of the board, you'll find two buttons, a capacitive touch logo, a microphone, and a 5×5 array of red LEDs that double as a light sensor. On the back you'll find the ARM chip, speaker, an accelerometer, a temperature sensor, and a radio antenna.

All of these built-in features can be accessed through MakeCode blocks. Now is a good time to explore them. Drag an **on button A pressed** event block into the workspace and nest a **show icon** block inside it — click button A in the emulator and your monster reacts.

Then try **on shake**, or **on loud sound** (v2 only), and pair each trigger event with something

TIME REQUIRED: 1-2 HOURS

DIFFICULTY: EASY TO INTERMEDIATE

COST: \$45-\$65

MATERIALS:

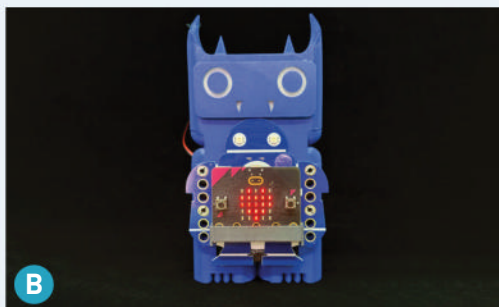
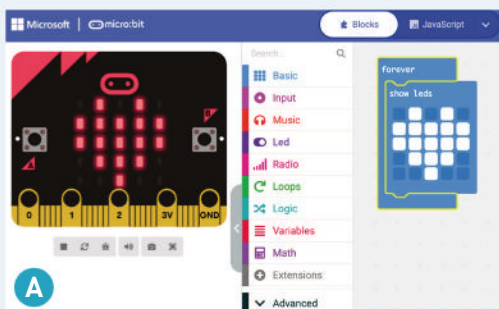
- **Make: Very Useful Monster RalfE kit, which includes:**
 - MakeyBit micro:bit board
 - micro:bit v2 mini computer
 - 3D-printed monster body
 - Eyes (2)
 - Lego-compatible pegs (4)
- USB micro cable
- AA batteries (3)
- Dupont connector cables, male-to-female
- LED, any color for Step 3
- Tactile pushbutton (optional) for Step 3
- Micro servomotor, SG90 or similar for Step 4
- Googly eyes and 3D-printed teeth/eyebrow pieces for Step 4

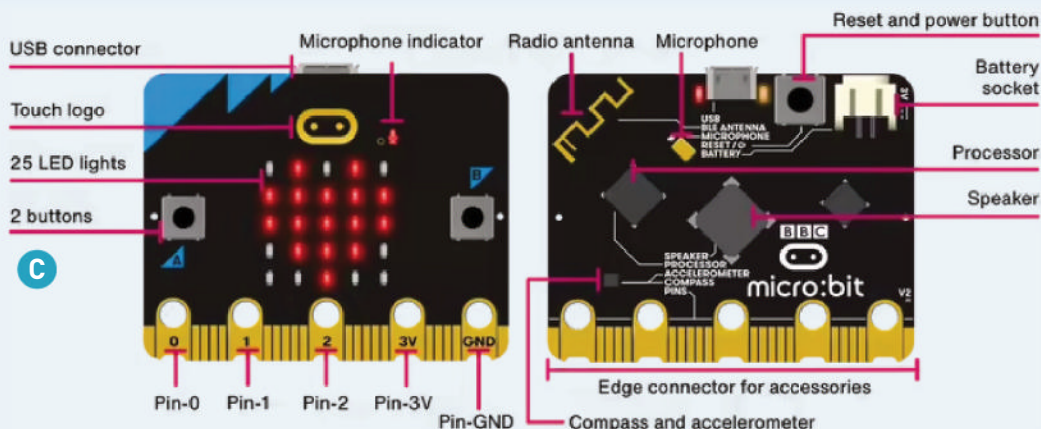
TOOLS:

- Small Phillips screwdriver and nut for Step 4
- Computer, Windows or Mac, with a browser



Grab your Make: Very Useful Monster RalfE kit at makershed.com/ralfe





from the Music or Basic categories.

This is a good moment to just explore. The emulator makes it fast to test ideas without uploading every time.

3. LIGHT UP THE EYES

The micro:bit can also control external hardware. Let's start simple — wiring up an external LED with an external switch. The micro:bit communicates with external components through pins — the labeled contacts along its edge. The MakeyBit breaks all these pins out into Dupont-style headers so you can plug cables in directly.

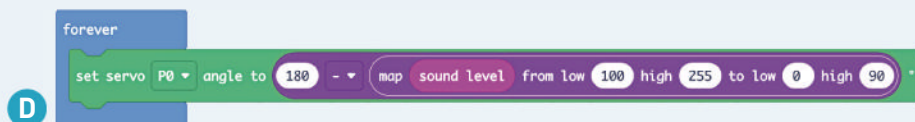
WIRE UP AN LED

Take a two-wire Dupont cable. Use red for signal and brown or black for ground. On the MakeyBit, locate pin 2, our signal pin, in the upper connector block, on the far left. Skip one hole, and the next is the ground pin.

Connect the LED: long leg (positive) to red, short leg to ground. Position it behind one of the pop-out eyes.

WRITE THE CODE

- Drag an **on button A pressed** block into your workspace.
- From Pins (under Advanced), add **digital write pin P2 to 1**.
 - 1 = on, 0 = off.



- Add a **pause (ms) 1000** block.
- Then add **digital write pin P2 to 0**.

Download and press A. Your monster's eye lights up for 1 second. To trigger from an external button instead, connect a tactile switch to pin 0 and ground (polarity doesn't matter for buttons), then swap **on button A pressed** for **on pin P0 pressed** from the Input category.

4. MAKE IT LIP-SYNC

Ready for something that'll get a reaction? In this step we'll add a micro servomotor that moves the monster's jaw and eyes in response to sound — making it look like it's lip-syncing every time you talk to it. Because the eye pieces are mechanically linked to the mouth, a single servo drives both at once.

CODE IT FIRST

Before touching any hardware, let's look at what the code does. Open a new MakeCode project and add the Servo extension (click Extensions and search for "servo").

The logic is straightforward (Figure D).

forever loop:

set servo at pin P0 to: 180 - map (sound level, 100, 255, 0, 90)

The **sound level** block returns a value from 0 to 255. We map the range 100–255 onto 0–90 degrees of servo travel, ignoring anything below

100 to filter background noise. Subtracting from 180 reverses the direction so the jaw opens when sound increases. The Math category include a **map** block that handles this directly — no manual arithmetic required.

SET THE SERVO STARTING POSITION

This step is critical: before attaching any physical pieces to the servo shaft, you must let the code set the motor to its starting position. Skip this and the mechanism can bind, stopping the servo from working.

Look at the back of the MakeyBit. You'll see labels: P0 servo A is on the lower row; P2 servo B is above it. Next to each pin label are battery and ground connections.

Servo cables have three wires. As a general rule across brands: brown = ground, red = power, and yellow or orange = signal. Plug the connector into the lower-left three-pin header with brown toward the right (ground side) as in Figure **E**.

Download your code, connect the micro:bit, and power on. Stay quiet — the sound sensor will move the servo if you speak. Let it settle at its start position, then power off. The servo is now in the correct position for assembly.

ASSEMBLE THE MECHANISM

Pop out both eyes from the monster body. You'll see a square hole (for the servo shaft) and a round hole beside it. Insert the servo into the body from the back, aligning the shaft with the square hole.

Take the eye piece with visible gears. It's slightly asymmetric — the thicker side goes down. Press it onto the servo shaft. Add the second eye piece and secure it with a small screw through the front, catching the nut from behind.

Snap on the teeth piece. Since the servo is in its start position (mouth closed), align the teeth to match a closed position.

Add googly eyes and snap on the 3D-printed eyebrow if you have one.

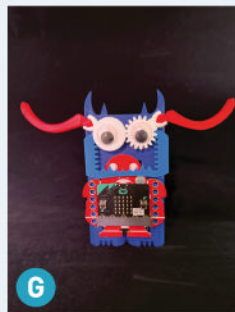
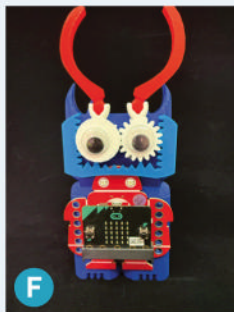
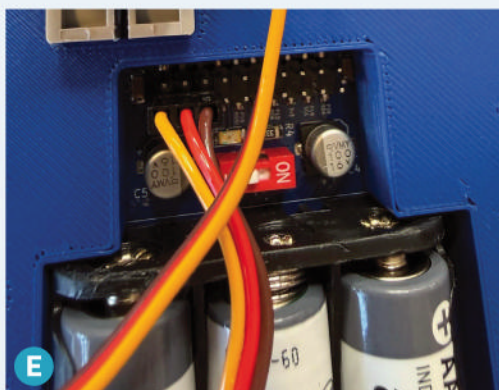
TEST AND TUNE

Power your monster back on and speak toward the microphone. The jaw — and eyes — should move with your voice (Figure **F** and **G**). If movement feels restricted, check whether the eyebrow or another piece is rubbing against the

ABOUT THE MAKEYBIT

The MakeyBit is a micro:bit extension board with an edge connector. It provides onboard power, and breaks out all the micro:bit's pins into Dupont-style headers, making it easy to connect LEDs, motors, buttons, and sensors — no alligator clips needed.

Lego-compatible pegs let you mount the board onto your 3D-printed monster body (or almost anything else). Learn more at makeybit.com.

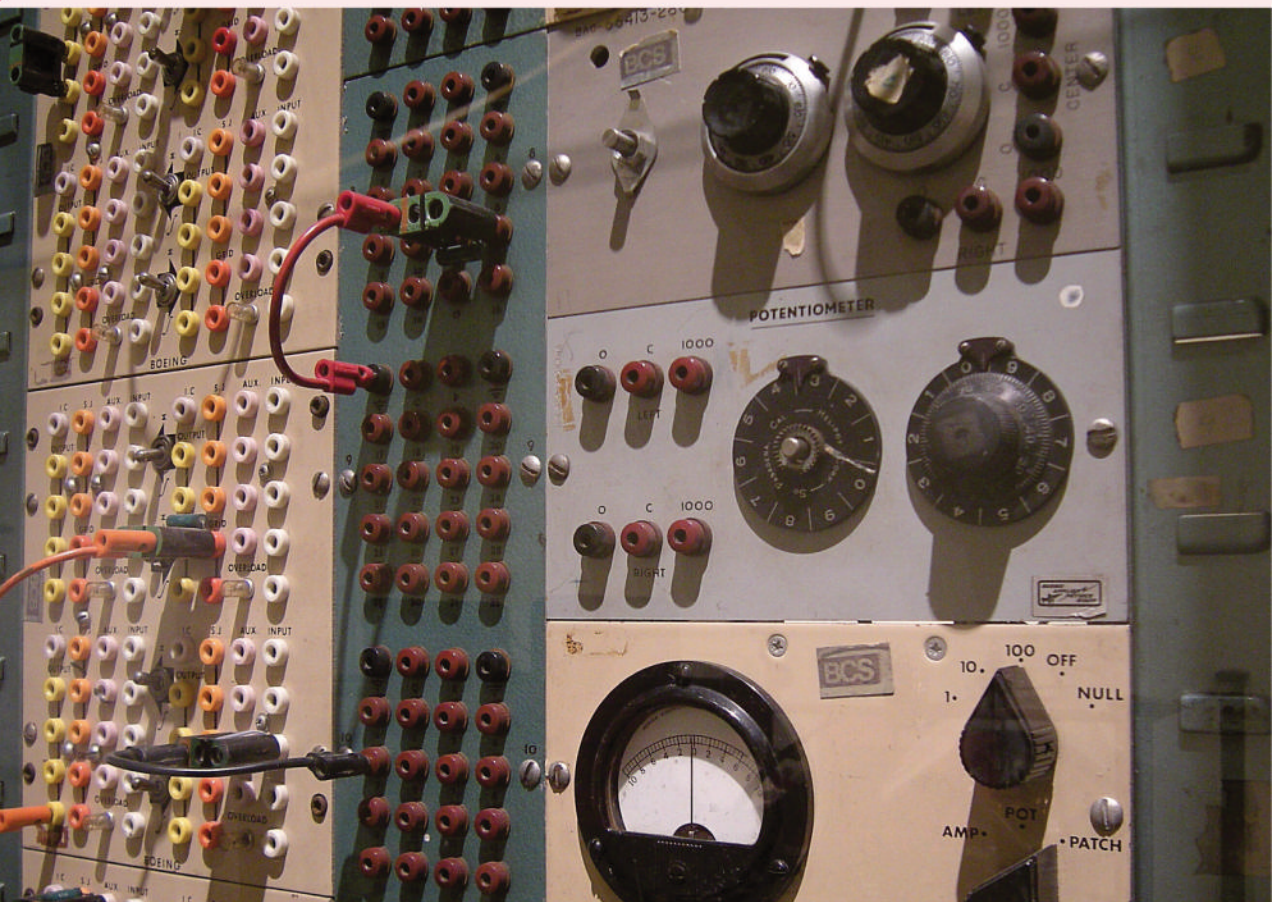


body. Remove the binding piece, reseal it, and try again.

To make the monster react only to louder sounds, raise the lower bound of the **map** block above 100. For more dramatic movement, increase the upper servo angle above 90.

GOING FURTHER

The Very Useful Monster curriculum continues with ultrasonic sensors, radio communication between monsters, and more — all using the same body for the canvas. And at every stage, it's still your monster. That's the whole point. 🐉



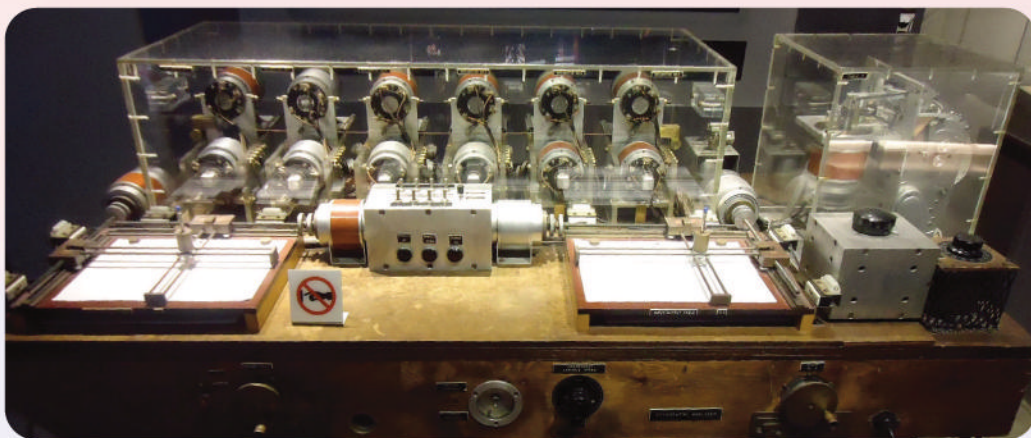
ANALOG COMPUTING

Why twiddling knobs and patching
cables can be smarter — and faster —
than programming lines of code

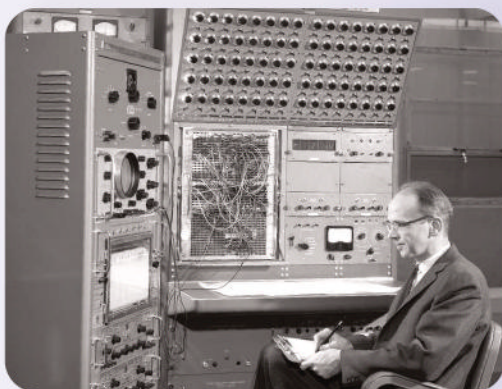
Written by Mike Bedford



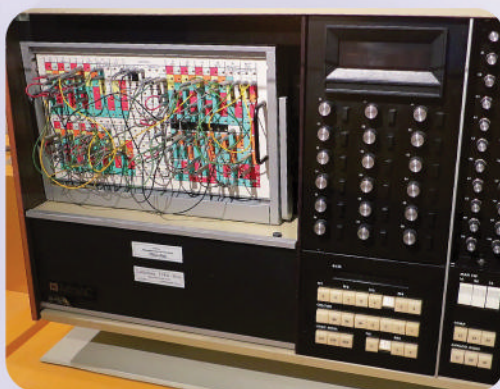
Like the vast majority of computing professionals, **MIKE BEDFORD**'s programming experience has been entirely digital. But he has dabbled with analog computers and found the process fascinating. Even so, he's not going to be swapping his PC for an analog computer anytime soon.



The first analog computing wasn't even electronic. Mechanical analog computers, like this 1956 differential analyzer, appeared as early as 1876.



This 1959 NASA photo certainly suggests that analog computing is antiquated, but it's a fascinating technology that may just have a place in computing once again.



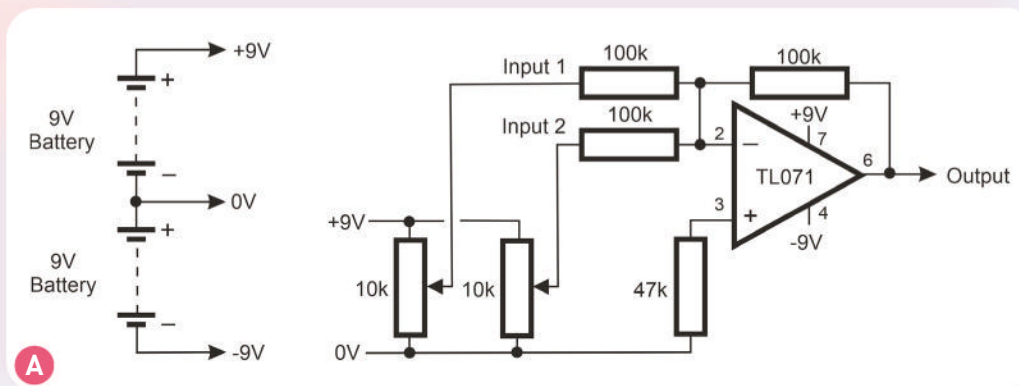
Analog computers weren't all massive beasts. Think of this MiniAC as the analog equivalent of today's PCs.

It's so much engrained in today's thinking that we don't normally prefix the word *computer* with the adjectives *electronic* or *digital*, but maybe we should — because computers haven't always been electronic, and even electronic computers haven't always been digital. In this article we're going to investigate electronic **analog computers** and show you how to get some hands-on experience with this alternative approach to computing. And this isn't just a history lesson, for although the heyday of analog computers might have been in the 1950s, 60s, and 70s, some researchers think they might soon stage a comeback.

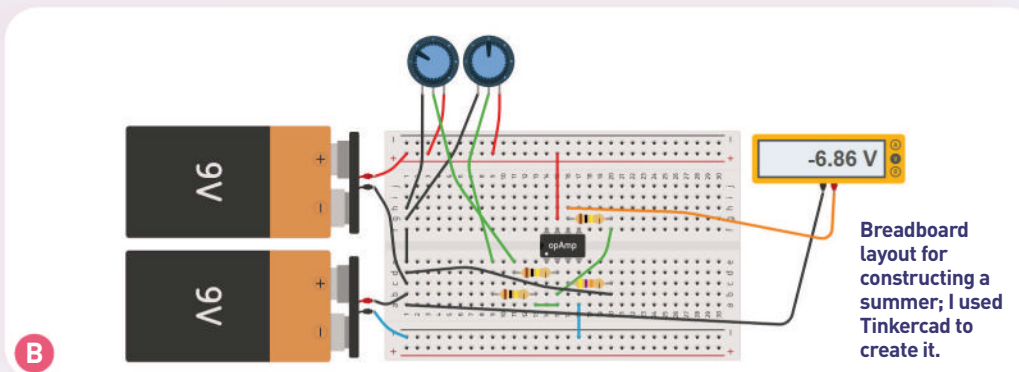
🌀 Digital vs. Analog

To set the scene, we'll paint a picture of how data is stored in a digital computer. A value is stored and processed as a binary number, with each bit represented as either 0 volts for a **0**, or a positive voltage — typically around 1 volt in today's processors — for a **1**.

All of that changes in an analog computer. Here a value is stored and processed as single voltage which is continually variable between two values, perhaps -15V and $+15\text{V}$. We saw this in *Make: Volume 83*, when Charles Platt presented an analog computing device that carried out calculations using analog voltages. Technically this was an analog calculator, because the output



Putting together this analog summer, together with two potentiometers for you to supply inputs, will help you get a feel for the analog approach.



was just a single value, but it leads into our first project here. This project lets you delve into the building blocks of an analog computer, by which we mean a device that, once programmed, outputs a series of values that represent the solution to a problem.

⚙️ Analog Building Blocks

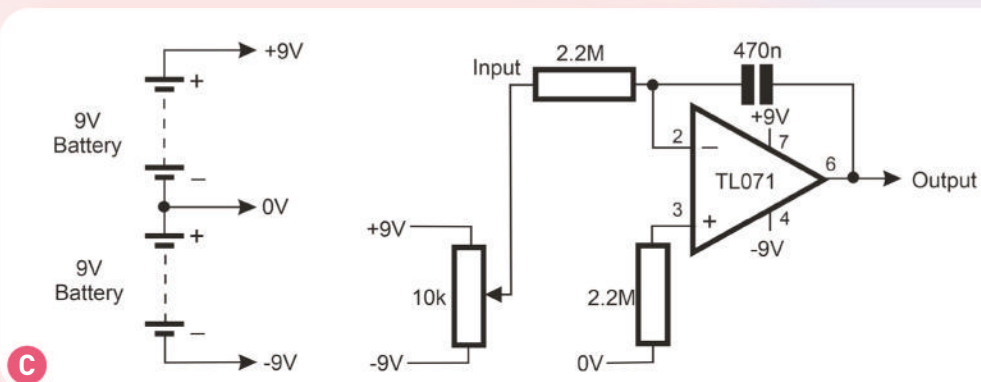
The most basic analog computers contain three types of functional units, namely **summers**, **integrators**, and **potentiometers**. You can easily build these units on a breadboard using just a few components.

A summer adds together two or more analog voltages to produce an analog output. Often summers had some inputs that had a gain of 1, and some with a gain of 10 which means that the input was multiplied by 10 before being added to the other inputs. Also, because of a quirk of the circuitry, the actual output was negated. So, for example, adding +1V and +2V would give an output of -3V.

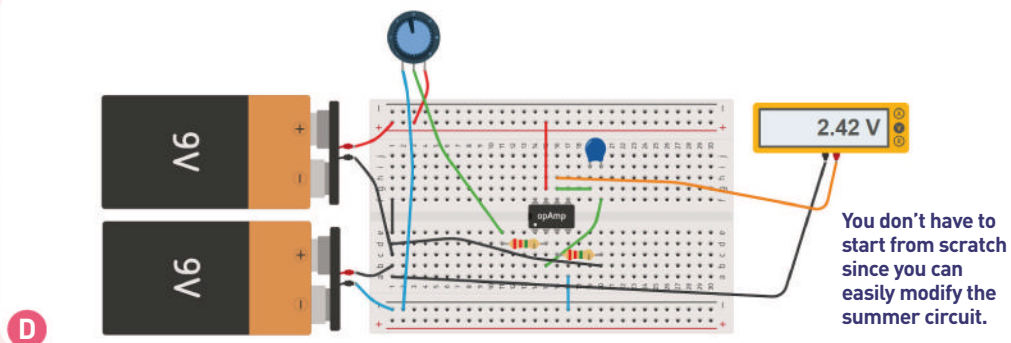
Before you can try out a summer, we need to introduce another building block that you'll need to provide an input to the summer. This component is the potentiometer, and it's a voltage divider, dividing a voltage by a constant value between one and zero. That value depends on the position of its rotary shaft, which would typically be fitted with a knob.

You don't need to build a potentiometer, as they're off-the-shelf electronic components. For your analog computer, all you need to do is wire contact 1 (the left-hand one as the shaft is facing you) to 0V, the input voltage to contact 3 (the right-hand one), and the output to contact 2 (the middle one). Potentiometers are differentiated by their resistance and, while this isn't too critical, we suggest 10kΩ. They are also available as linear or logarithmic versions — use linear ones.

Our summer (Figures A and B) has just two inputs, both with a gain of one. The component shown as TL071 is a chip called an *op-amp* (operational amplifier) and there are lots of



Once you're *au fait* with the summer, you only need to learn about the integrator, which you can easily do by building and exercising this circuit.



types available. If you choose a different type, the pinouts could be different, and some types contain two or four op-amps in a single package instead of the one in a TL071. When you've finished hooking it up and giving it a good check, turn both potentiometers fully counterclockwise to give both summer inputs a value of 0V, and connect the positive and negative power supplies. The summer output to your voltmeter should be 0V. Now start rotating one or both of the potentiometers clockwise and you'll see an output equal to the negated sum of the inputs.

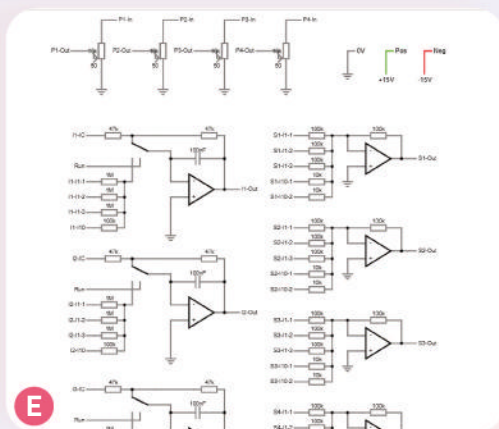
Now to an integrator (Figures C and D) which, like a summer, usually has multiple inputs which are added together before the integration takes place. Again these can have a gain of 1 or 10. Our integrator has just one input with a gain of 1. We show the potentiometer wired differently from those in the summer circuit so you can generate negative voltages (fully counterclockwise), zero volts (center position) or positive voltages (fully clockwise).

In broad terms, here's what an integrator does. If the sum of its inputs is zero then the output won't change. If the input is a constant positive value, the output of a true integrator would ramp up but, because the op-amp circuit used in analog computers has inverted outputs, it'll actually ramp down. And with a constant negative input, a true integrator's input would ramp down but ours will ramp up. The speed at which the output changes is proportional to the value of the input.

Programming Analog Computers

Real-world analog computers have lots of these three basic components, and programming involves wiring several of them together to solve a particular problem. Analog computers are used for simulating complex systems in the real world. Simulation involves solving differential equations and is one of the hardest types of problem that today's supercomputers were built for.

In his introduction to analog computing, Platt



This portion of our analog computer emulator in the Falstad circuit simulator shows the four potentiometers plus a few integrators and summers.

introduced The Analog Thing (THAT), an open design for an analog computer that you can buy as a kit. If you get serious about analog computing this is surely the way to go, but it'll cost you several hundred dollars. As a cheaper and more accessible way to learn about analog programming, we present a zero-cost solution in the form a build-it-yourself emulator. We use a free circuit simulator called Falstad (falstad.com/circuit) which you can run on the Falstad website or download to run on your PC. It's fairly intuitive to use and a user manual is available.

Having already seen the circuitry for the basic elements, you won't learn much more by defining an analog computer from scratch in Falstad, so we're providing a circuit definition file (*Analog Computer.txt*, available at makezine.com/go/analog-computer) for you to input to Falstad (Figure E). We will say a few words about the circuit though.

The summer and potentiometer circuits are similar to those we showed earlier. However, the integrators are different because, for any real-world problem, there must be a way of setting up their initial conditions, that is, the value of their outputs before the program is run. To do this, integrators have two modes, **Run mode** and **Initial Conditions (IC) mode**, which are selected by a **control signal**. The control signals for all the integrators are supplied from a single mode switch so they'll all be in the same mode at any time. In IC mode, the integrator outputs are equal

to the negated value of an IC input.

The other thing you need to know about analog computer circuitry — and hence of our emulated circuit — is that all summer, potentiometer, and integrator inputs and outputs are wired to sockets on a **patch panel**. The user can then forget about the internal workings of the building blocks and simply program the computer by plugging wires into sockets on the patch panel and adjusting the potentiometers. Falstad's potentiometers are slider controls to the right of the screen.

You'll also need some way of viewing the result which, on a real analog computer, would involve patching an oscilloscope or pen recorder to the output of the relevant summers and/or integrators. A time plot can be displayed in Falstad by right-clicking on a point on the patch panel and then selecting one of the scope options from the menu. By default the scope will display both voltage and current, but we're only interested in voltage, so right-click on the scope, select Properties → Plots from the menu, and deselect Show Current.

With your emulated analog computer in place, you can now program it to solve a problem! Our example exercise is to simulate the change over time of the vertical position of a weight on a spring, its oscillations diminishing due to friction. This is defined by the following two differential equations in which V is the velocity of the weight, Y is its vertical position, and f is a constant related to the amount of friction.

$$\frac{dV}{dt} = -fV - Y$$

$$\frac{dY}{dt} = V$$

In a first-order differential equation, dx/dt means the rate of change of x with respect to time, and integrating this gives a value for x . The wiring diagram to solve this problem, as analog programmers of old would have shown it, is shown in Figure F. The circles are potentiometers, the triangles are summers, and the triangles with rectangles on their left sides are integrators. The numbers next to the inputs of summers and integrators are the gains of those inputs. From this diagram you should be able to work out how to patch up the analog

computer but, if you want a shortcut, input a new circuit definition file (*Spring.txt*) into Falstad. This will load our analog computer circuit with the spring model already wired up on the patch panel (Figure G). To start, we suggest setting Potentiometer 1 to 50% and Potentiometer 2 to 100% but you can change them later.

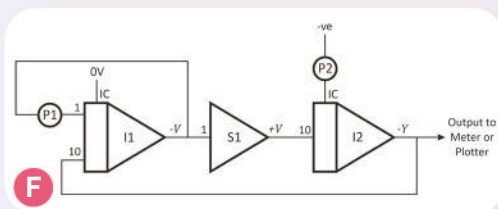
The computer will be in Initial Conditions (IC) mode to begin with so, as soon as the green trace on the graph has stabilized, click on the Mode switch below the panel to put it in Run mode and you'll see the damped harmonic motion of the weight. Our solution actually computes $-Y$ but if this offends you, just wire another summer between the output of I2 and the meter/plotter. If you use a gain 1 input on the summer it'll behave as an inverter so you'll end up with Y .

If you fancy solving another problem from scratch, how about trying the SIR model which simulates the spread of an infectious disease? You'll easily find details online, for example at people.wku.edu/lily.popova.zhuhadar.

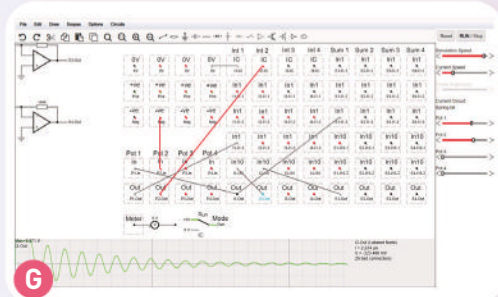
Ⓢ Analog Computers Today

Despite their retro feel, there are signs that analog computers could stage a comeback, but this time with a difference. Unlike digital computing, where the time taken to carry out a simulation increases with the number of differential equations, the time stays the same with analog computing; so for some problems, analog computers can be quicker. They also use less power. On the downside, programming an analog computer can be much more difficult than coding a digital computer. You can't just load a new program from disk, you have to patch it up again by hand.

Modern analog computers could provide the best of both worlds: analog circuitry working hand-in-hand with digital. First, the digital computer works out how the analog building blocks should be wired together to solve a particular problem. Then those connections are made, not by a hand-wired patch panel, but by electronic switches under the control of the digital computer. And finally, the results are passed back to the digital computer for display, storage, and/or subsequent processing.



This wiring diagram, with traditional analog computing representations for potentiometer, summer, and integrators, solves the “weight on a spring” problem.



Patch panel in Falstad shows wiring needed to solve the same problem. At bottom is the result — a graph of the position of the weight against time.



German firm Anabrid makes analog-digital hybrids, including this Lucidac computer for robotics. Says founder Bernd Ulmann: “It learns to touch my hand gently.”

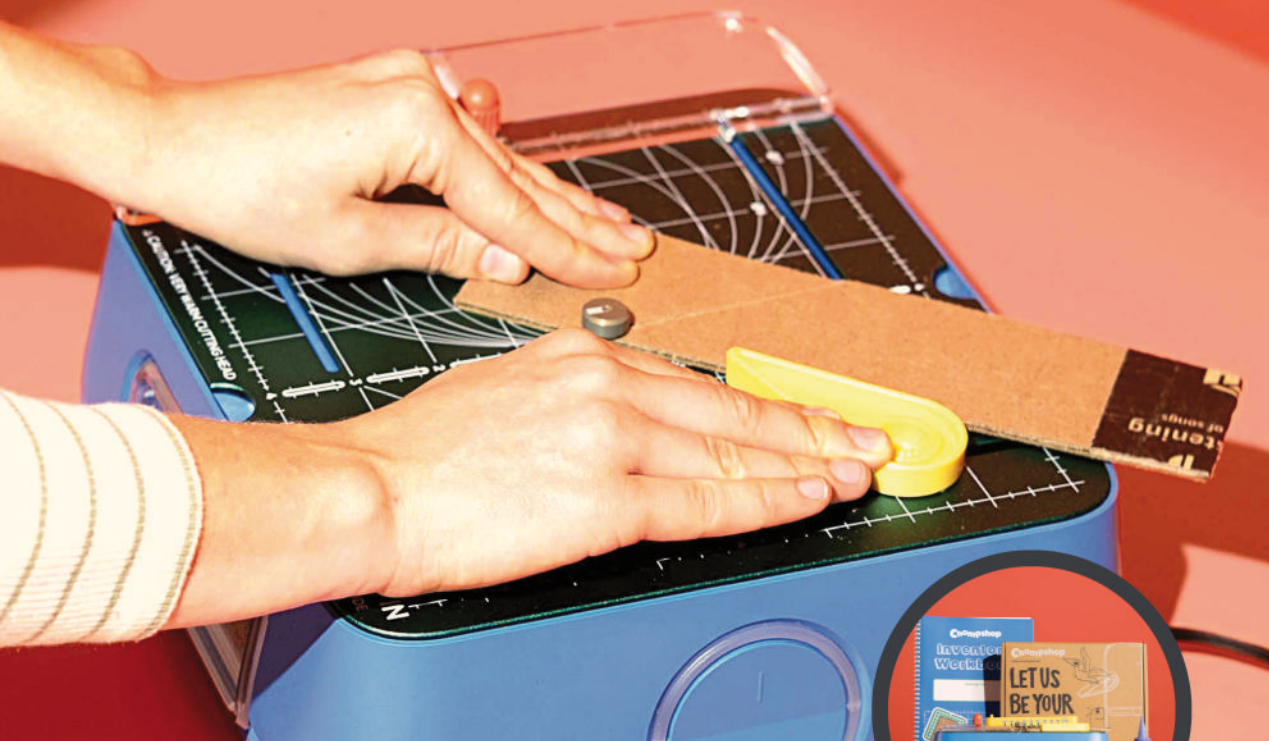


Well-funded startups like Mythic are already building analog chips for AI, promising to vastly reduce energy needs.

Analog computers aren't as accurate as digital, but not all problems require digital accuracy and, in such cases, the speed and reduced power consumption of analog could be paramount. An analog co-processor can find a reduced-accuracy solution very quickly before handing over to the digital computer to home in on a solution to the necessary precision. Sounds like it wouldn't be wise to write off analog computation just yet. 📌

TOOLBOX

GADGETS AND GEAR FOR MAKERS Tell us about your faves: editor@makezine.com



ChompSaw \$249–\$299 (as reviewed) | chompsaw.com

Sure, the ChompSaw — the kid-safe, desktop power tool for cutting cardboard — looks amazing in the ads flooding social media. As an adult who designs educational handmade paper inventions and simple robot projects, I was itching to see if the ChompSaw could help me bring power tools to my books, videos, and classes.

But a kid's-eye view was clearly needed, so I carted my sample ChompSaw and accessories down to my local library. Within minutes, 4-year-olds mastered the straight cut and moved on to curved designs of their own making. A ninth grader wondering how it would work on other materials tested it out on a plastic folder. The ChompSaw handled it all. It was cool to see preschoolers and library staff alike fall into a meditative state as they steadily pushed cardboard toward the cutting head.

Best of all? No Band-Aids required. The ChompSaw works like a high-speed precision

hole puncher, nibbling small bites out of the cardboard you feed it. Fingers cannot reach the cutting mechanism, and it is safety-certified for ages 3 and up. The machine comes assembled and has a solid feel. The plastic base stores the power cord and dust collection drawer. The heavy metal lid flips between inch and centimeter marks. And the chunky on/off toggle switch is good for small hands. The accessories are equally well thought out, with hand tools for punching holes and scoring folds, and an alternate metal lid that helps you cut circles or line up an angle.

The only flaw I noticed was the dusting of chomped cardboard that collected around the cutting head. I shook it out at regular intervals. The Chompsaw site also suggests ways to prevent the machine from sliding around when cutting extra-thick cardboard. But all in all, I think ChompSaw lives up to the hype. It's a gateway power tool for designers of any age. —Kathy Ceceri



READ
THE FULL
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COM!

xTool M2 Color Craft Laser

\$749 (as reviewed) | xtool.com

The M2 Color Craft Laser combines a diode laser cutter and a CMYK inkjet printhead for new possibilities in automated customization. To switch from printing to cutting, you just pop out the inkjet head, swap in the magnet-mounted laser module, reconnect the USB-C cable, and you're good to go. It takes seconds.

The built-in tutorials are a great way to get up and running. An extensive material library delivered excellent results. And the spring-loaded magnetic fixture tabs made for easy and precise placement.

Dual cameras can monitor whole jobs at once or get close up for precise positioning. The 16"×12" bed fits a lot of small parts.

I can think of a few spot-on applications for this machine, starting with book nooks and jigsaw puzzles. But the capability is applicable to any project that needs post-laser coloring. Adding an inkjet to a laser means there's no need to use single-line fonts or try to wrench graphics out of CAD software.

The M2 fits xTool's continued focus on production for small business owners. The CMYK and laser toolheads complement each other well, making it a chocolate-and-peanut-butter combination of desktop machines.

—Sam Freeman



Cytrence Kiwi+

\$119 | cytrence.com

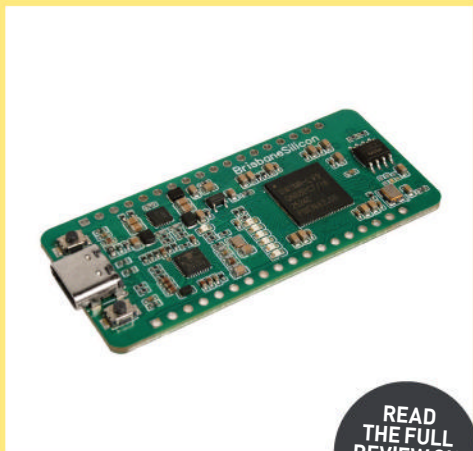
It's awkward to modify headless Raspberry Pi projects. I have played around with SSH, VNC, and just editing the SD card on a laptop, but all these have drawbacks. For simple and foolproof Pi hacking, there's the Cytrence Kiwi.

Kiwi turns your laptop into a KVM (keyboard/video/mouse), so your Pi doesn't need a bulky external keyboard, monitor, and mouse setup. Just connect HDMI and USB to the target machine, and a USB 3 cable to the host, and you can watch the target boot up, no network connection needed.

Setup was fast and easy, and felt basically like working on the target Pi. I didn't try the latest first-person shooter, but inputs were responsive enough for simple games.

The Kiwi+ comes in three different versions depending on your needs. Kiwi+ Drive doubles as removable flash storage to transfer 32GB by virtually mounting and remounting the drive. Kiwi+ Net creates a link between devices to move giant batches of data. And Kiwi+ USB lets you connect a backup drive, sensor, camera, or other USB peripheral.

All of the sample units worked painlessly with Mac, Linux, and Windows. They even let you copy and paste text from laptop to Pi — perfect for boards too RAM-deficient for Chromium. If you regularly manage headless computers, the Kiwi could make your life so much easier. —SF



READ
THE FULL
REVIEW ON
MAKEZINE.
COM!

ELM11

\$15 | brisbanesilicon.com.au

The ELM11 is a nifty and useful Lua-based platform which, although new and evolving in terms of toolchains, already provides a surprisingly polished developer experience.

ELM stands for Embedded Lua Machine. It's more efficient than Python, in the familiar Feather form factor. Powered by a Gowin FPGA, it allows low-level control with multiple hardware overlays.

The IDE grants a comprehensive and user-friendly solution to work with the board, though I still found myself feeling cool diving right in over serial to get things done over either its REPL or higher level CLI.

Lua feels particularly well oriented to the embedded world, and the system BrisbaneSilicon has laid out seems to showcase that well. You can even change the underlying system between the Lua runtime and the hardware via uploadable hardware overlays and modules, enabling customized CPU frequency, pinout configurations, LED indicator behavior, and more.

With the \$15 price and the effort that BrisbaneSilicon has put into the experience, I could see the ELM11 being in projects all over, especially in education or prototyping.

—James Koenig



PolyCast5

\$119 | polycast5.com

PolyCast5 is an open source multitool for controlling wireless devices. Created by Justin Atkins of RoboticWorx and powered by an ESP32-C5, it packs in five different types of signals: Wi-Fi, Bluetooth, LoRa, ESP-NOW, and IR. There's also an optional AC relay that can switch mains devices on/off. And I²C pins are accessible for add-ons.

The preview model was a bunch of fun. The device was surprisingly hefty, and the color screen was sharp. It can clone IR, manage passwords, sniff Wi-Fi packets, and accept voice commands. An auto keyboard can type over Bluetooth, and the Rickroll example does exactly what you would expect.

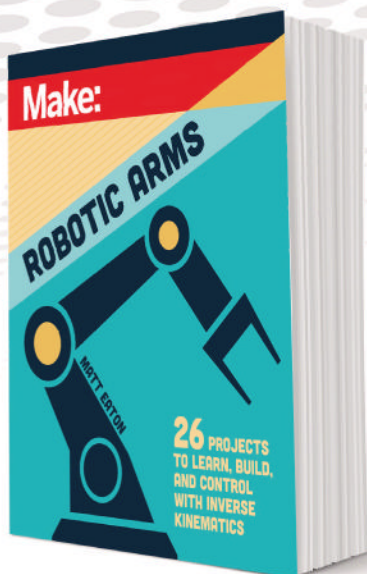
PolyCast5 comes with a few offline apps, including a pomodoro timer. I thought it would feel like a gimmick, but it turns out having a vibrating, pocket-sized focus timer on a device with no apps is genuinely useful.

The deauth attack did what deauth attacks do, and was a little concerning. A Wi-Fi sniffing function lets you bring up MAC addresses on nearby networks, and that was enough to discover that someone nearby had a Roku. I named a couple of other nearby devices before I was told to stop being creepy.

It also runs *Doom*. —SF

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Arduboy FX-C

\$79 | arduboy.com

Arduboy, the credit card-sized game console, keeps evolving, now with the FX-C. It's still pocket sized and still powered by an 8-bit ATmega32u4. Though the power is tiny compared to the ubiquitous ESP32, it still sports a library of 300 community-made games and counting.

It's small and light enough that I forgot I was carrying it around, and the monochromatic screen is bright enough to play outside. An RGB LED adds a hint of color.

Unlike those 50-in-one systems-on-a-chip with five games and 10 minor variations on each, these are actually 300 individual games. The effect is something like *UFO 50* in a universe of pocket LCD games (though saying *UFO 50* is like Arduboy might be more accurate). There are twists on old classics and new originals, so yes, you can play *Snake*, but also addictive faux-3D games.

The beauty of the system, of course, is that you're not limited to what it comes with. The open source console is a platform to learn how to code your own games and apps, with excellent tutorials written by the community. If you can program an Arduino, you can make your own wallet-sized game. —SF



KeyboaStick

\$0-\$17 | makerworld.com/@FunOrNothing

The KeyboaStick by FunOrNothing instantly makes a boring keyboard fun, and a fun keyboard awesome.

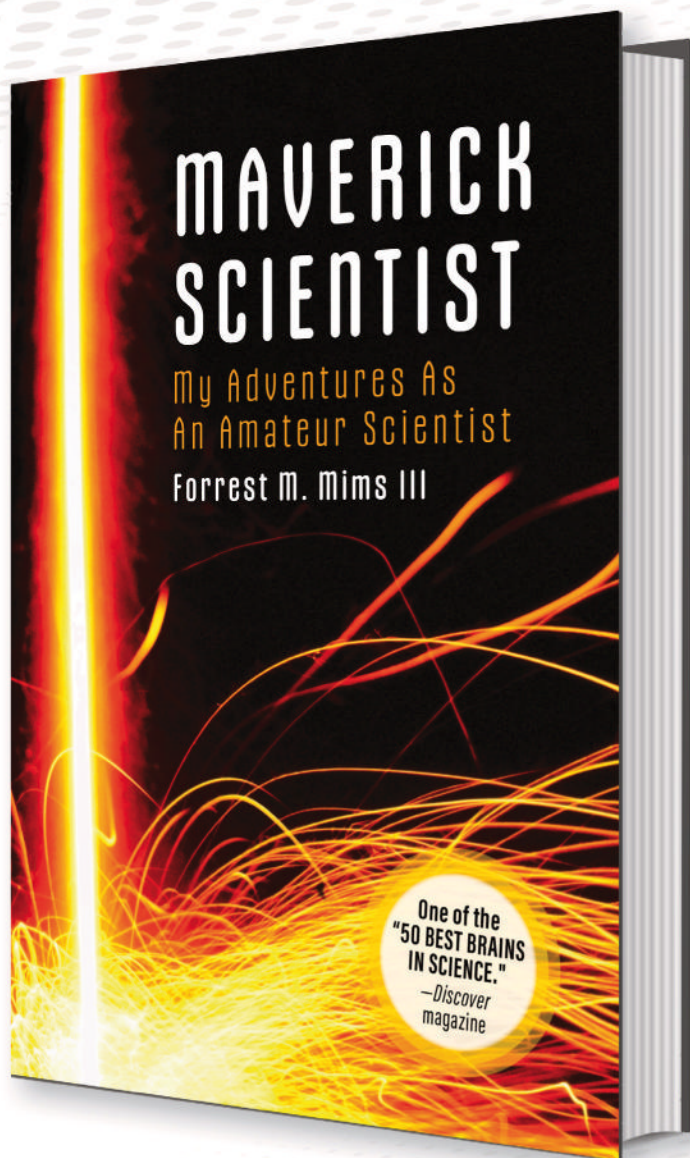
It's a well-designed model that comes in various flavors. The standard version replaces WASD keycaps and turns them into a tiny joystick. The joints mostly print in place, and it's designed so forgivingly that it prints out well on older, not-perfectly-calibrated machines.

Assembly is straightforward; even with no post-processing the parts fit together well. And though the movement felt a little sticky aiming to the side, and I got so excited I pulled off the top, I still was able to make it through *Sonic the Hedgehog 2*'s Emerald Hill Zone without the controller being a problem.

The design has been stolen a lot, but you can still download the files on MakerWorld or buy finished prints from the official RadianLab store on Etsy. There are versions for other keys, and a quick-replace version as well. A redesigned Pro version with even better performance is available as a physical print from the RadianLab Etsy shop.

I do blame it for getting a Game Over in Chemical Plant Zone, but it's possible that says more about my skills. —SF

Did you know Forrest Mims is a ...



- Maverick Scientist who **forged his own scientific career** without any academic training in science.
- As a teen, he **invented a new method of rocket control**, and **designed and built an analog computer capable of translating Russian to English**.
- He **created a hand-held radar-like device to guide the blind** while still attending Texas A&M University.
- While in the military, he was **granted special clearance for top secret laser research at the Air Force Weapons Lab** despite lacking engineering credentials.
- He **co-founded MITS** which produced the **first commercially successful personal computer**, and designed the circuit that became known as the infamous **Atari Punk Console**.
- He later **consulted for NASA's Goddard Space Flight Center** and was **given the Rolex Award** for his achievements.



Forrest's memoir provides an intimate look into the scientific community and tells the story of lifelong learning.

Limited edition hardcover copy available today at Maker Shed.

makershed.com/maverick

Make: Books



Bob Seif

Making Your Mark

Bob Seif will be at Maker Faire Bay Area in September, bringing with him a 6-foot-long mechanical pencil that uses 10mm lead. He calls it the “world’s largest mechanical pencil.”

Bob grew up in the suburbs of New York City before he went to Purdue University in Indiana. He thought he’d be a design engineer but after several internships, he decided he wanted to work more with people than things.

He created his giant mechanical pencil as an homage to the humble writing implement. “It’s one of the few pieces of technology that we use every day,” he says of it. His giant pencil is fully functional, with a spring and clutch that he built himself. He got the 10mm graphite from McMaster-Carr.

The one thing he didn’t make was a large eraser. He’s just not into chemistry, he said. “Making my own eraser would be hard.”

When Bob applied to Maker Faire, he had already decided how he’d exhibit the giant pencil. “I’m going to see if people can write something with it,” he said. He will have a large roll of paper and invite people to try out holding and writing with the mechanical pencil. I liked that Bob was thinking about how he could not just display his

giant creation but also interact with people by having them try to use it.

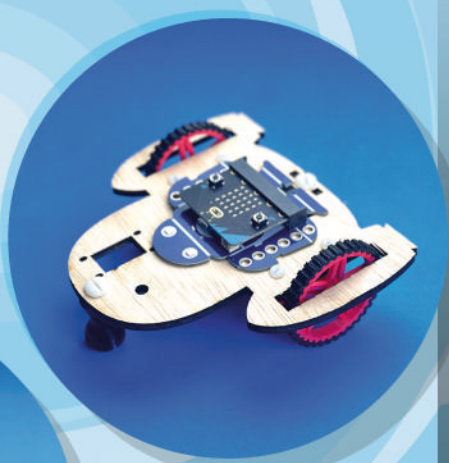
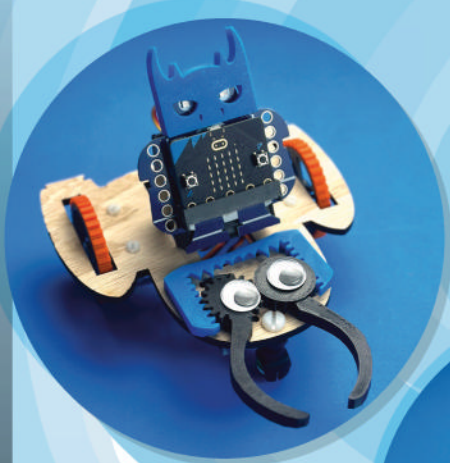
He’s also a fan of letter writing. “I write lots of letters and I really like doing that,” he said of an analog activity that has its own novelty in the age of email correspondence.

I asked Bob why he’s exhibiting at Maker Faire. He replied: “I want to show people that they can make things.” He said it’s fun to show his work but he wants to “encourage and empower others by letting them know they are capable of making things.” He appreciates that that’s what Maker Faire is all about.

Bob’s next project is going to be his own digital wristwatch. He wants the entire case to be a capacitive sensor that will turn off the watch with a single touch.

I noticed he was wearing an analog wristwatch, and I asked him why he wants or needs a new kind of wristwatch. He said that a co-worker who comes to see him always stares his watch. “While we are talking, he’s figuring out how much more time he has to spend with me.”

Bob finds that annoying. His new wristwatch design could help solve that pesky, interpersonal problem. —Dale Dougherty



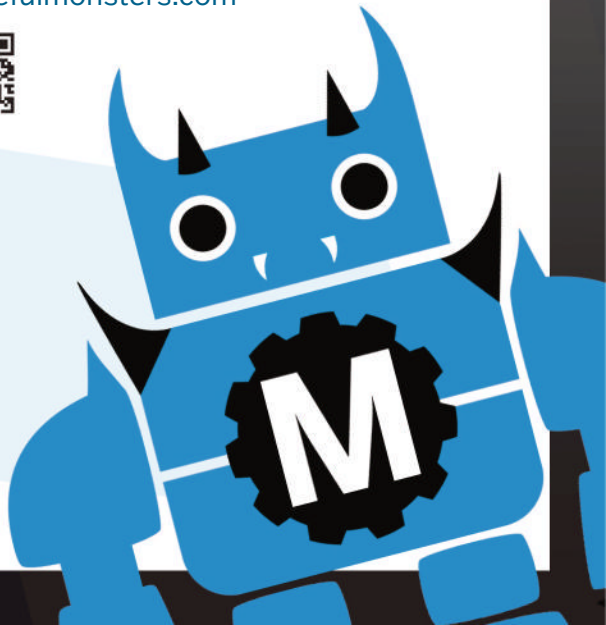
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