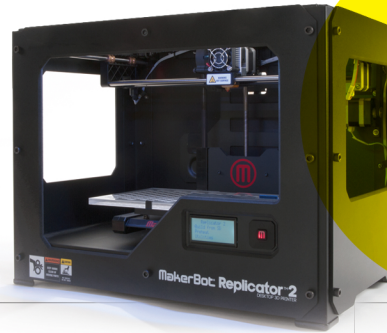


3D PRINTER BUYER'S GUIDE

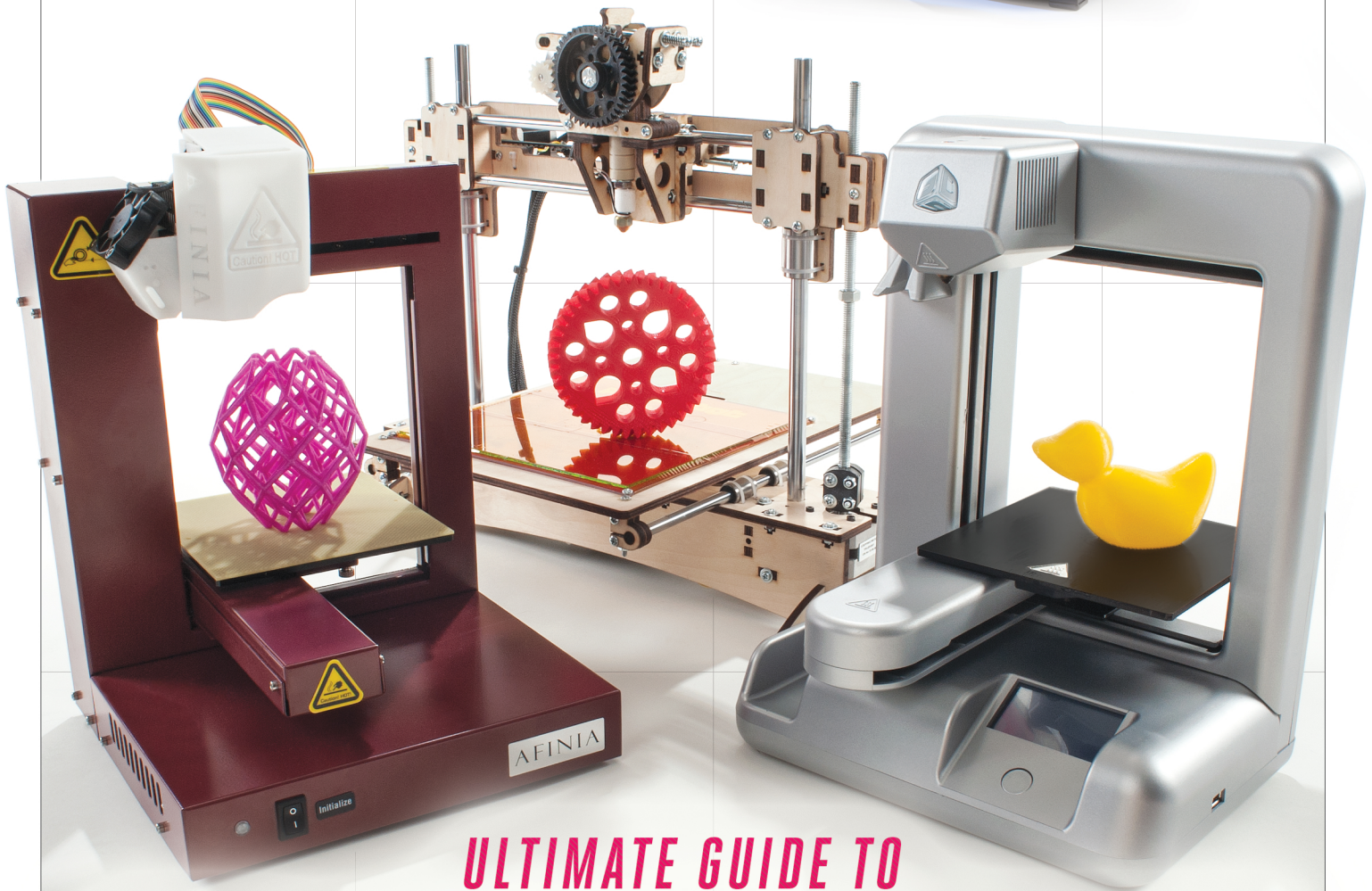
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OPTICAL TREMOLO BOX

Plug your guitar into light-programmable waveforms with this unique effects box!

Tremolo—it's that pulsing undulation of high and low volume that makes music sound like it's being played underwater or through a spinning fan.

Made famous by 1950s guitarists Bo Diddley (who actually used a fan in front of his amp), Duane Eddy and Link Wray, the tremolo sound saturated '60s surf and garage rock, and was revived in the '80s by players like Poison Ivy Rorschach (The Cramps) and Jimmy Wilsey (Chris Isaak). You've heard it in hits by Pink Floyd ("Money"), The Smiths ("How Soon Is Now?"), R.E.M. (pick a song on *Monster*), Rage Against the Machine ("Guerrilla Radio"), Green Day ("Boulevard of Broken Dreams") and the Black Keys ("Howlin' for You").

When MAKE contributing editor Charles Platt wrote about DIY tremolo and fuzz guitar effects in MAKE Volume 15, he proposed a Hypothetical Tremolo Wheel that would vary the volume based on how much light fell on a photosensor.

Well, it's hypothetical no more. I took Charles' cue and built this Optical Tremolo Box, which reads a patterned disk with a light sensor to create tremolo effects that you can custom-program with any pattern you like. It's a great project for anyone who likes music, guitars or electronics, and it's like no effects box you've seen before.

HOW DOES IT WORK?

Open up the cable that connects your electric guitar to your amplifier, and you'll find two wires—one "ground" and one held at positive voltage relative to ground. The changing electrical potential between these two wires is what carries the sound signal. If you short-circuit these wires, the sound goes away, because the charge finds its way home, without bothering to go all the way through your amplifier.

But what if you bridge the two wires with a variable resistor? You have a volume control: turn the resistance way up, and the sound stays loud; turn it way down, and the sound vanishes down the short-circuit path. And here's where Charles had his clever idea: use a variable resistor that responds to light! If you put a photoresistor behind a spinning transparent disk with opaque bands on it, then the volume will follow the shadow pattern on the disk, repeating as it spins. And that's tremolo—a repeating variation in volume.



PARTS

- Project enclosure, 6"x3"x2" #270-1805
- Adhesive label, 8 1/2"x11"
- Rheostat, 25Ω #271-265
- Resistor, 15Ω #271-1102
- Solder #64-017
- Control knobs (2) #274-018
- Hookup wire #278-1224
- Potentiometer, 10K #271-1721
- Photoresistor, 6mm #275-1533
- LED holder #276-080
- Switch, DPDT #275-1533
- Double-sided foam tape
- DC power jack, size M #274-1563
- Audio jacks, 1/4", mono (2) #274-280
- Motor, 1.5V-3VDC #273-223
- Plastic tubing from ballpoint pen
- Wood screws, #4x1/4" (2)
- Flexible LED flashlight, Coast model TT7578
- Rubber grommet, 3/8" ID, for 1/2" hole #64-3025
- Transparency film, 8 1/2"x11"
- Terminal strip, 8-position #274-678

See the project page (online) for additional parts.

The Optical Tremolo Box is simple to build and sounds great. A rheostat controls the tremolo motor speed, while an audio potentiometer controls the tremolo intensity. You can customize the disks with any pattern you want and create tremolo effects that have never been heard before.

It also looks pretty cool, with its flexible LED light and spinning disks. Build it and I guarantee your friends will want one!

— Sean Ragan, MAKE Technical Editor

To see full build instructions, wiring diagrams, disk art and project photos, visit the project page for this build:
radioshackdiy.com/project-gallery/optical-tremolo-box.

Parental supervision is strongly recommended when using power tools and solder. Always wear safety glasses. Avoid breathing fumes and always work in a well-ventilated area. Wash hands thoroughly after use. Follow all safety instructions on solder and soldering equipment packaging. California residents: WARNING: Soldering products contain, or when used for soldering and similar applications produce, chemicals known to the state of California to cause cancer and birth defects (or other reproductive harm).

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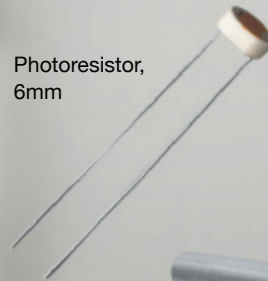


Audio jack, 1/4"

Motor,
1.5V-3VDC



Photoresistor,
6mm



Potentiometer, 10K



Rheostat, 25Ω



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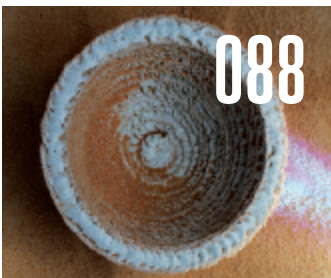
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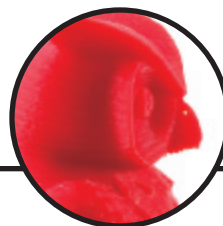
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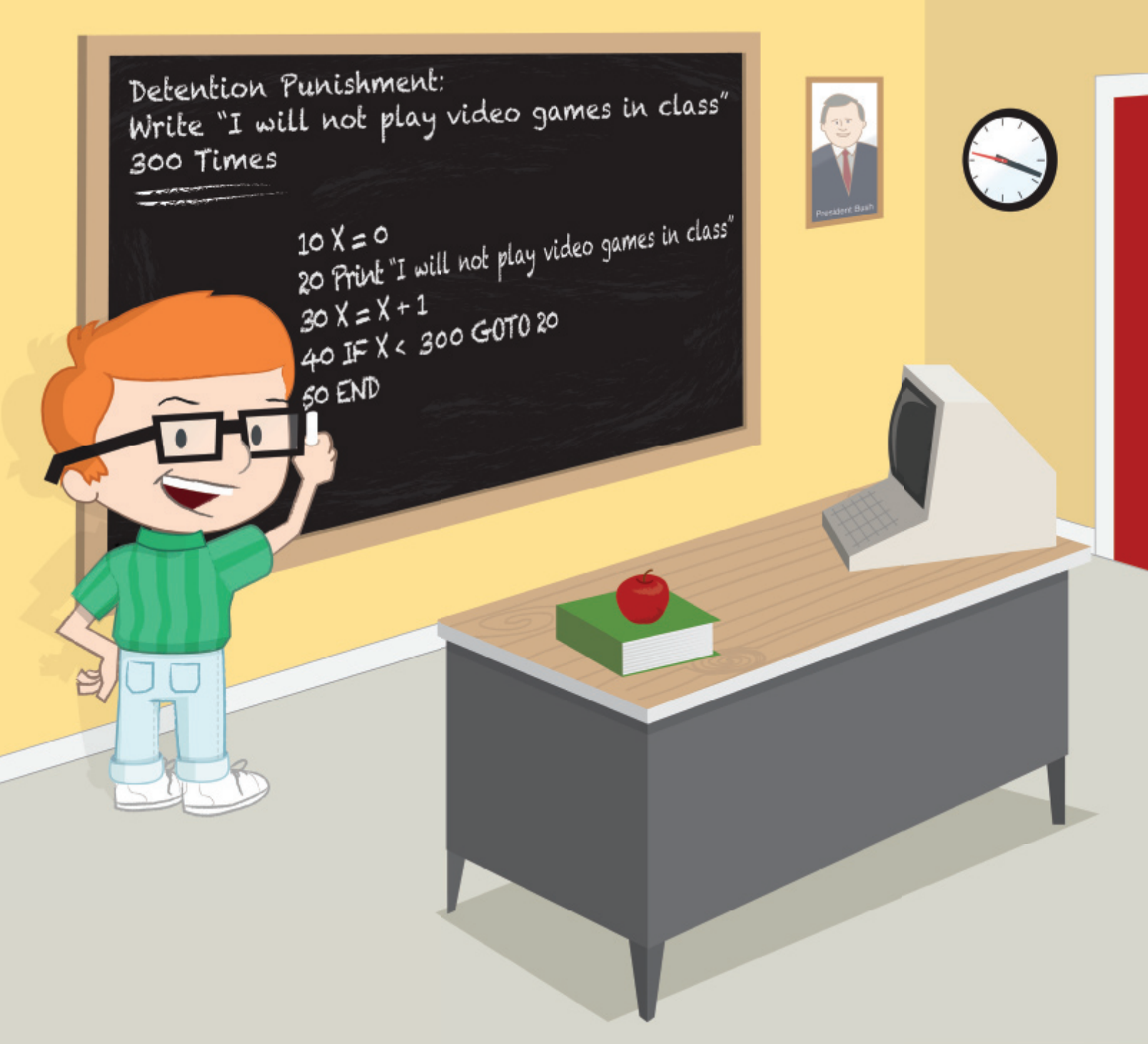
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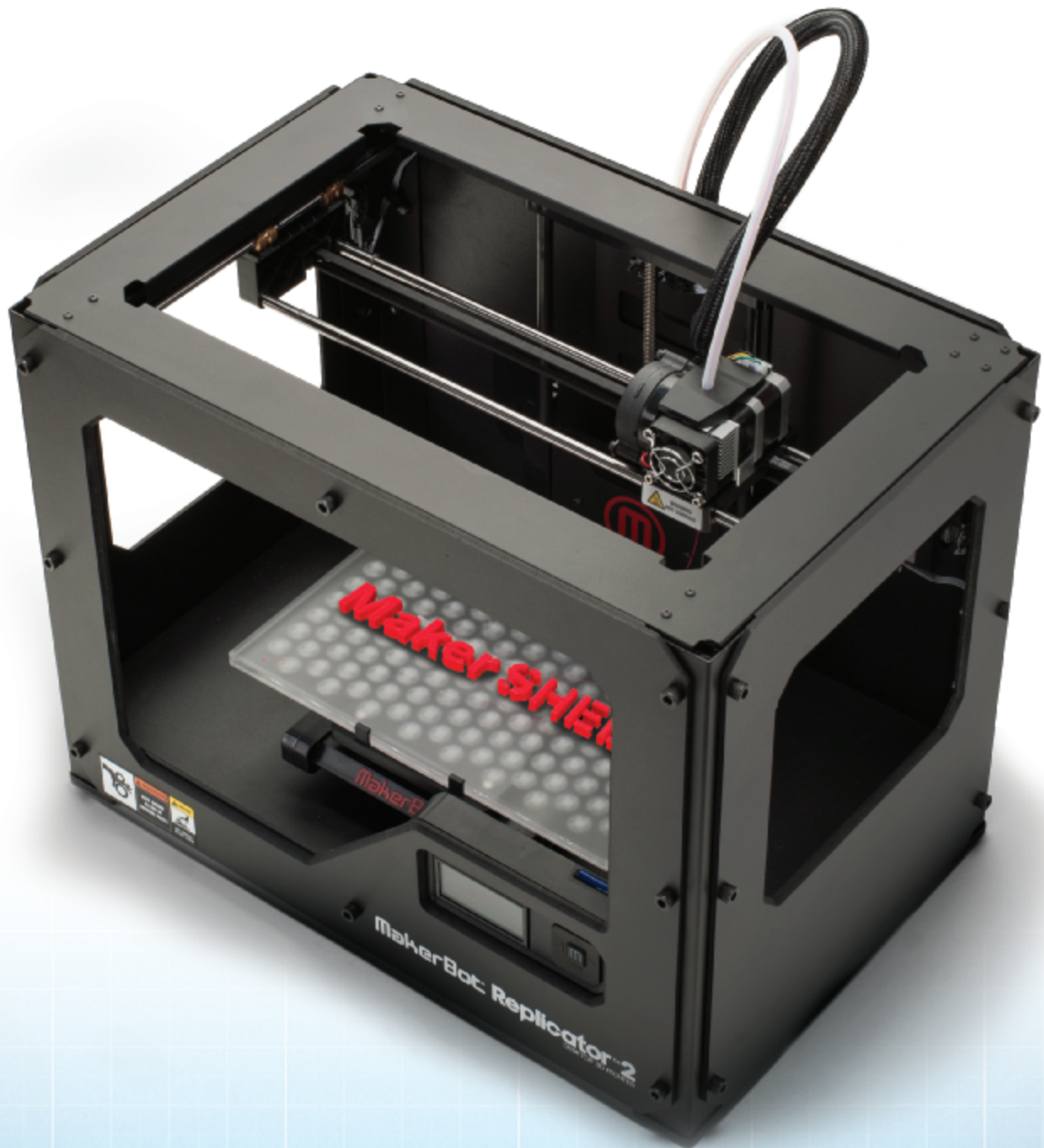


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DREAMING OF 3D PRINTERS

A new wave of affordable machines is democratizing 3D printing.

▶ **AT A RECENT TALK AT NEW YORK UNIVERSITY JUST BEFORE WORLD**

MAKER FAIRE 2012, I asked the audience, mostly undergrad and graduate students, how many of them had 3D printers. None of them raised a hand. Then I asked how many wanted a 3D printer, and all the hands in the room shot up. Immediately.

The market for personal 3D printers is still in its early stages but it's becoming very hot. The dream of 3D printers stirs our imagination.

The challenge for personal 3D printers is to make them practical and affordable to do what we dream of doing. At the same time, the challenge for anyone who justifies spending a couple thousand dollars on a 3D printer is to dream of something more interesting than duplicating colorful, plastic tchotchkes from Thingiverse.

Several years ago MakerBot Industries released the Cupcake CNC 3D printer as a kit that makers could build for themselves, starting off the personal 3D printing revolution. Before that, commercial 3D printers were industrial machines for a highly specialized design market. MakerBot founders Bre Pettis, Adam Mayer, and Zach "Hoeken" Smith adapted and simplified open source technology developed in the RepRap community and produced a working model with a homely laser-cut case. Sure, it might've taken weeks to put this model together, but makers could realize their dream of owning a 3D printer.

Like the first personal computers, 3D printers were signposts for an unsettled territory, awaiting the pioneers to explore the future.

MakerBot is still the leader in personal 3D printing, announcing the all-black, ready-to-run Replicator 2 in September. They have

a strong brand and a vibrant community. Yet the announcement caused shock waves with its mixed message about the openness of the platform. Built on the contributions of the open source hardware community, MakerBot signaled that they needed to "lock down" some of the designs and software in order to remain competitive and prevent others from cloning them.

WRITTEN
BY
**DALE
DOUGHERTY**

A new crop of 3D printers, many of them crowdfunded as Kickstarter projects, are providing more options for buyers, but the competition is also confusing. In the early days of a new product category (think MP3 players), many different models compete, offering varied design choices. Each model introduces new features, testing what users want and what they're willing to pay for. Eventually the best features will be consolidated into a few surviving models. Yet before that happens, we can enjoy the variety of prototypes and their experimental nature.

To help you choose among these new machines, we put together a team of experts to test and review 15 desktop 3D printers on the market today. We learned an enormous amount, and we're confident you will too in our Buyer's Guide beginning on page 38.

I also enjoy learning more about the makers of these new models. Diego Porqueras of Pasadena, Calif., developer of the Bukobot, told me he read Volume 21 of MAKE, which featured Bre Pettis on the cover, and decided to build a 3D printer himself, relying on general skills he acquired in metal shop and computer science classes. Diego raised \$167,410 on Kickstarter from 290 backers.

Few of these 3D printer makers have specialized expertise, or vast amounts of capital, but they have the determination to do something they really believe in — and their belief is democratizing 3D printing.

Getting more people to use 3D printers is not just about getting the hardware right. Many of our 3D printer testers commented that the software needs to be better. The problem is certainly the lack of a polished user interface for many open source software tools.

The challenge for personal 3D printers? To make them practical and affordable to do what we dream of doing.

But there's another problem. We have to learn to design in 3D. Turning our ideas into 3D objects that are suited to production on a 3D printer demands more of us than just clicking the Print button. In this guide, we'll show you how to design 3D objects easily in Tinkercad (page 30) and how to prep 3D models captured by Kinect or 123D Catch (page 92). All of us will require training, along with the energy and enthusiasm of makers like Riley Lewis, a high school freshman in Santa Clara, Calif., who says he first picked up 3D printing in sixth grade. Now Riley teaches workshops in 3D printing at area schools and has been a guest blogger for 3D Systems, makers of the Cube printer.

Riley reminds me of another dreamer with a practical mind, Ben Franklin, the apprentice printer who was the prototype American maker. I'd like to know more about what Riley dreams of doing, and I look forward to seeing what makers are actually doing with 3D printers.

Dale Dougherty is the founder and publisher of MAKE.

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THE PROMISE OF 3D PRINTING

Printing the world on your desktop.

▶ IT'S A VISION FROM A FUTURISTIC STAR

TREK UNIVERSE: effortlessly creating three-dimensional objects on a machine in your home (or starship). And it's here today. The dam has now burst on the 3D printing market and this once out-of-reach technology is now available to just about anybody, for less than \$1,000.

Will being able to print 3D objects on your desktop change the world?

Spend a few minutes talking to manufacturers of 3D printers or early adopters and you'll quickly hear them drop such heady adjectives as "game-changer," "disruptive," and "revolutionary."

An *Economist* article from April 2012 by Paul Markillie declared 3D printing and associated technologies nothing short of the "third industrial revolution."

"As manufacturing goes digital, a third great change is now gathering pace," he writes. "The wheel is almost coming full circle, turning away from mass manufacturing and towards much more individualized production. And that in turn could bring some of the jobs back to rich countries that long ago lost them to the emerging world."

The personal computer, the printer, and the internet made us all publishers. Now with 3D printers, 3D scanners, and 3D design software, we can all be manufacturers, as well.

Already companies are jockeying for position. High-end 3D printing pioneer 3D Systems bought competitor Z Corp. Two other big players — Objet and Stratasys — are planning to merge. Industry darling MakerBot was named one of the top 20 startups in New York City and was one of Fast Company's 2012 Innovation by Design awardees.

3D printers, machines that "print" three-dimensional, CAD-rendered objects by layering precisely extruded bits of molten plastic,

resin, metal, and other materials, have actually been around since 1985 — ironically the same year the standard-setting HP LaserJet printer was introduced. The laser printer has become as commonplace as the personal computer. The same can't be said of the 3D printer. But that could be about to change.

WRITTEN
BY
**STETT
HOLBROOK**

Until recently, 3D printers were prohibitively expensive, less than user friendly, and hidden behind the doors of factories and R&D labs. But thanks to the innovative efforts of makers and the open source movement (which encourages freely sharing designs and software among enthusiasts), the price of the machines has reached the consumer level. Now, a growing community of makers, designers, and artists are embracing the technology and taking it in new directions. And, you don't have to own one of the machines to use them. There are service providers that will do the printing for you. What you do with all this desktop manufacturing power is up to you.

To borrow a line (paraphrased from Karl Marx) from *Wired* Editor-in-Chief Chris Anderson's book, *Makers: The New Industrial Revolution*, power belongs to those who control the means of production. The power to manufacture a growing list of objects (toys, jewelry, spare parts, even prosthetic limbs) is now available to the masses — and the technology fits on your desktop.

"Global manufacturing can now work on any scale," Anderson states, "from one to millions. Customization and small batches are no longer impossible — in fact, they're the future."

He too sees revolution in the air: "The third industrial revolution is best seen as the combination of digital manufacturing and personal manufacturing: the industrialization of the maker movement."

Looking at the growing number of

consumer-level 3D printers on the market has Anderson seeing 1983 all over again — the so-called "Mac moment" when Apple gave the masses a computer of their own: the Apple II. Apple didn't invent the computer, they just democratized it, Anderson notes. The same can be said of RepRap and MakerBot, two pioneers in the affordable consumer 3D printer market.

"A new class of users will produce a new class of uses," says Anderson. "I think it's historic."

Will 3D printers become as common in the home as DVD players and computers? Wonky software and documentation are the weak links now, but that will surely change.

For now, Anderson tells parents this is the year to buy their kids a 3D printer for Christmas.

"They're not going to be quite sure what to do with it, but their kids will figure it out. That's the way big things start."

Dale Dougherty, founder and publisher of MAKE, isn't ready to pronounce the 3D printer a revolution just yet.

"I think we're at the very early stages, with hackers and early adopters figuring out what to do with it," he says. "It's opening new avenues for people who are creative and making things."

But the transformative potential is plain to see, Dougherty states. "It's Wal-Mart in the palm of your hand. That's the crazy promise of it."

Part of the excitement that surrounds 3D printing is the belief that now the barrier to entry has dropped; the genie is out of the bottle. Where this goes, nobody knows.

"We live in a 3D world, but we currently create things in 2D," says Dougherty. What will it mean to have the means to live and create in the same dimension?

"We may go to a very different place."

Stett Holbrook is a senior editor at MAKE.

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WHEN LESS IS

MORE

WRITTEN
BY
TOM OWAD

The takeaway on milling vs. 3D fabrication.

- ▶ **THERE'S A LOT OF WELL-DESERVED EXCITEMENT** surrounding 3D printers, and for the avid DIYer much of it is focused on their ability to “self-replicate” by making their own parts. But is a 3D printer the right tool for you?

A 3D printer’s fabrication technique is additive — most of them use a hot plastic extruder to “print” a plastic model. This contrasts with subtractive fabrication tools, which start with a solid block of material and use a cutter to remove the excess. Subtractive fabrication is far more common than additive, especially when working with metal and wood. Lathes, mills, saws, and drills are all subtractive tools.

DIY CNC

Going with milling doesn’t mean you have to give up on self-replication or on making your own machine. Patrick Hood-Daniel makes a scratch-build CNC kit capable of making all of its custom parts, just like the RepRap 3D printer and its progeny. The frame is built of custom-cut plywood. Everything else is standard hardware.

The aluminum angle, bolts, and screws are available from any hardware store. The lead-screws and anti-backlash nuts will probably have to be mail-ordered from McMaster-Carr and DumpsterCNC, but you can get by with lesser hardware store parts in a pinch. The stepper motors and stepper drivers are completely generic and available from countless sources. The spindle is an ordinary wood router. I use a Porter-Cable 892.

As with the RepRap, the trick with Patrick’s CNC router is getting a seed unit. Fortunately, any CNC router that can handle a 2’x4’ sheet of plywood is capable of making the parts. Check out your local hackerspace, TechShop, and even the MAKE forums or the Home Shop Machinist, and you’re likely to find somebody local with the necessary equipment. (If you can’t find anybody to cut the parts for you, Patrick sells several kits.)

To get the CAD and CAM files for the parts, go to buildyourcnc.com/cnckit2.aspx and download the plans for the CNC Routing Machine Kit Version 1.3. Videos on the website explain how to put everything together. The files are licensed under the Creative Commons Attribution-Noncommercial license, which means you can make machines for yourself and for your friends, but you can’t sell them commercially.

The CAM files are in the proprietary CamBam format, but there’s a free version available, and it can read and write DXF files. Most good CAM software is very expensive, though, so if you don’t already have a favorite, stick with CamBam. It can do both CAD and CAM, and even the free version is tremendously full-featured.

Another exciting new option is the MakerSlide system, available from Inventables (inventables.com). Perhaps the most significant weakness in the BuildYourCNC design is decreased rigidity and precision due to its wooden design. MakerSlide integrates V-rails into what is otherwise a standard aluminum extrusion system (available from 80/20, Misumi, and others). By building your machine out of a combination of MakerSlides and stock aluminum extrusion, it’s possible to create a more rigid, precise machine than you could with wood.

A CNC milling machine or router is the subtractive equivalent to the 3D printer. For the hobbyist, milling is inferior to printing in numerous ways:

» Milling inherently causes waste, and without some sort of dust control, that waste gets flung throughout the room.

» Milling is more dangerous — while it's possible that a plastic extruder might overheat and catch fire, I've already had a (minor) fire with my CNC router, and there's the added danger of a blade, spinning at 20,000rpm, sending bits of itself, or even your workpiece, flying at you.

» A mill or router is necessarily larger and heavier, and consequently more expensive and more difficult to move. It requires a positioning system that can maintain accuracy when encountering resistance, and motors powerful enough to drive it.

» Software preparation is also more complex for milling. After drawing the object you wish to make in a CAD or 3D modeling program, it's necessary to generate toolpaths with CAM (computer-aided manufacturing) software. This involves

specifying the dimensions and location of the stock material, the dimensions and characteristics of the end mill (cutter), and speeds for the axes and spindle. The tools to do this tend to be complex, and a bit daunting for the first-time user.

From the user's perspective, CNC milling is a much more complex process than printing is. CNC milling does, however, have a significant advantage over 3D printing: the technology is mature. Home 3D printers are improving at a tremendous rate, but there's often still a lot of tinkering and experimentation involved in getting a good print.

WHAT DO YOU WANT TO MAKE?

If your interests tend toward larger and more structural creations, go with milling. Also consider that it's cheaper to work in wood than in plastic, and that you're likely to get substantially superior results.

On the other hand, making complex 3D objects is a lot more complicated with CNC milling than with a 3D printer. There are free tools for doing 2.5D milling (the z-axis never

moves when the x- and y-axes are moving), but CAM software for 3D milling is very expensive and difficult to use.

Doing 3D work for 3D printing is much easier. You can design your models in a free program like SketchUp or Inventor Fusion, and then export an STL file. Skeinforge software converts the STL file automatically to tool paths in G-code, then Prinrun software sends the G-code directly to your 3D printer. With 3D printing, there's no need to tweak cutting paths, and no worry about the tool crashing into your work.

If creating small 3D objects is your goal, a 3D printer is the right choice.

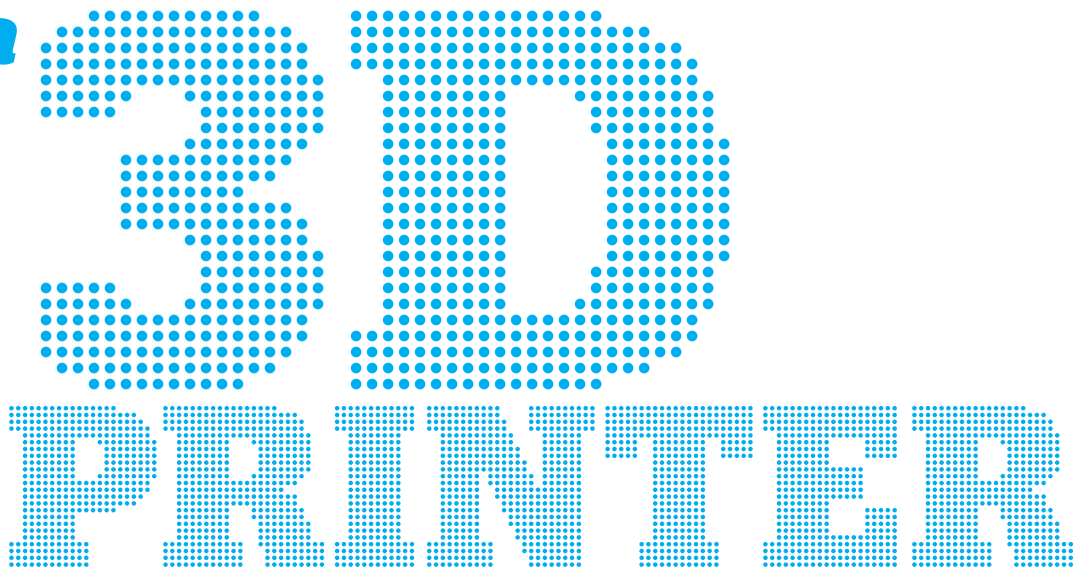
One final tip: If you can't decide whether you want to do CNC milling or 3D printing, start with milling. A 3D printer isn't designed to handle the stresses of milling, but a mill can be easily retrofitted to support a plastic extruder for printing.

Tom Owad is a Macintosh consultant in York, Pa., and editor of Applefritter (applefritter.com). He is the author of *Apple I Replica Creation*.



GETTING STARTED

with a



WRITTEN
BY
**BILL
BUMGARNER**

Are you interested in buying one? Read this first.

► **EARLY IN 2012, I PICKED UP AN ULTI-MAKER**, put it together, and joined the growing ranks of 3D printing households. It has been an adventure both filled with reward and rife with frustration. The goal of this article is to share what I've learned while studying the DIY portion of the 3D printing realm. The focus is on budgets less than \$2,500, with a goal of producing parts out of various kinds of plastic.

Plastic parts are wonderful for prototyping. You can print that engine part in plastic, make sure it fits perfectly, and then send the 3D model off to a company like Shapeways to have your prototype turned into a production piece in the metal of your choice (see prototyping sidebar, right).

Most of the printers discussed here are hackable. Their designs are amenable to being modified and tuned to fit your needs. The software used to drive these printers is almost all open source, though there are

commercial slicers and modelers commonly used in the 3D printing community.

CHOOSING A PRINTER

The 3D printers discussed here are of the *additive manufacturing* variety. They create parts by adding material together and are the new hotness in the field of manufacturing. So hot, in fact, that the Obama administration created the National Additive Manufacturing Innovation Institute (NAMII) to foster innovation in this field.

There are three approaches to additive manufacturing in common use: *photopolymerization* (using light to cure a liquid material into solids of the desired shape), *granular materials binding* (using lasers, hot air, or other energy sources to fuse layers of powder into the desired shape), and the focus of this article, *molten polymer deposition* (MPD; extruding molten material in layers to build up the desired shape).

In short, MPD, aka fused deposition modeling (FDM) or fused filament fabrication (FFF), describes pushing a filament of solid plastic (or other materials like metal or chocolate) into a hot-end that then extrudes a thin stream of molten material in layers to build up the desired piece.

Of these technologies, MPD is the most common and most accessible (though EMSL's CandyFab definitely bears mention because any printer that smells like crème brûlée deserves a shout-out).

Focusing on MPD, there are a handful of different styles of printers. The differentiation is largely focused on exactly how the printer moves the extruder to a particular point to extrude the plastic.

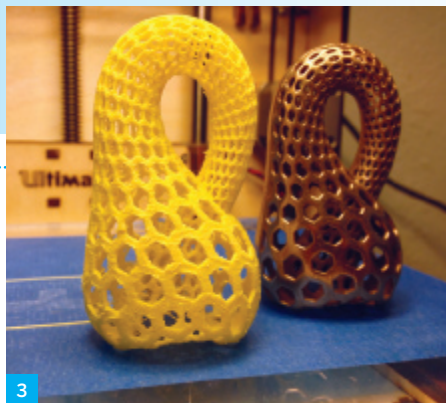
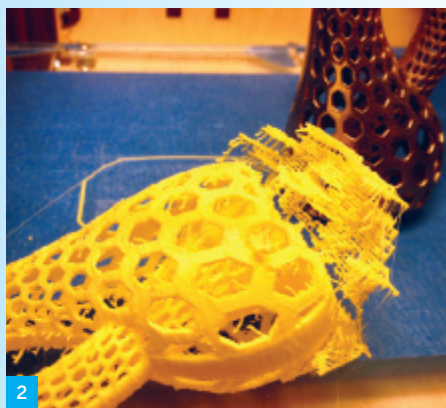
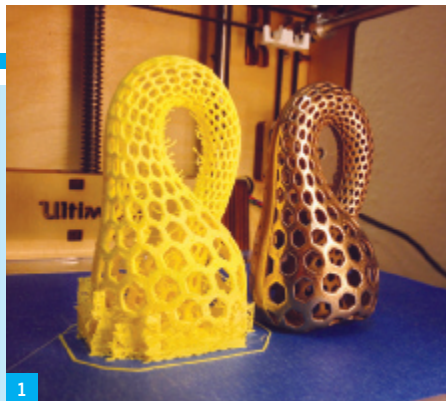
BUYING OPTIONS: TURNKEY, KIT, OR DIY

With this information in hand, it's time to choose a printer! There are many turnkey

PLASTIC PROTOTYPING

Bathsheba Grossman's beautiful (and incredibly popular) Klein Bottle Opener is a perfect example of the prototype-in-plastic, print-in-metal process that allows for lots of cheap plastic drafts before committing to the relatively expensive process of procuring a finished metal part. On the left is a 3D print of Grossman's bottle opener. On the right is the same model printed in stainless steel and brass from Shapeways. You could tune and print the model all day long for very little money (less than \$1 in plastic per print) and then commit to the metal version once fully satisfied with geometry, fit, functionality, etc.

1. A draft print of the Klein Bottle Opener still attached to the print bed with the support visible at the bottom.
2. Removing the support.
3. The finished draft beside the final piece.



3D print can be summed up as *model* (or *capture*), *fixup*, *slice*, and *print*. At each step, there are multiple software solutions to choose from.

» **Generating STL files** *STL files* are the lingua franca of the 3D printing world. If an application can export a 3D model as an STL file, then that STL file can be sliced and printed. STL files can be generated using a *CAD program*. SketchUp (sketchup.com) is quite popular, as are a number of open source 3D modelers. On Mac OS X, Autodesk has released Inventor Fusion (labs.autodesk.com/technologies/fusion), which combines significant power with a relatively easy-to-use package. Both are free.

Regardless of which modeler you choose, expect the learning curve to be steep. The key challenge is to translate what you want to make into a set of primitive shapes and elements in the modeler, such that the result is possible to print. For example, any overhang shallower than about 45° cannot be printed without support material (which consumes material that will be tossed, increases print time, and requires significant cleanup) because the plastic will sag (the actual angle varies from printer to printer and depends on how you configure the slicer).

Alternatively, models can be generated using a *parametric CAD program*, of which OpenSCAD (opencad.org) is quite popular. Instead of drawing what you desire, you write code in a simple language that tells the CAD system what you want.

Many of the mathematics-targeted packages like Mathematica can also produce STL files.

Models can also be generated from photographs or videos. Autodesk's 123D Catch (123dapp.com/catch) can process a series of photos and turn them into a 3D model (see *page 92*). With an iPhone or iPad, you can take up to 40 pictures of a model using 123D and then upload them to a server that processes the images into a 3D model. Note that Autodesk also released 123D Make (123dapp.com/make), which slices 3D models into plans for constructing the model out of cardboard or paper.

Often the model for what you want has already been created by someone who shared it online. The most popular repository for pre-made models (and full-on projects) (*cont. on page 16*)

solutions that go well beyond our targeted price range. And there are some that are quite affordable. The Up 3D printer (same as the Afinia H-Series, see *page 44*) is an example of a "ready-to-print" device that requires relatively little maintenance. The MakerBot Replicator is similarly focused, but is both more versatile and may require a bit more maintenance.

A word of warning: when buying a turn-key printer, be wary of "razor vs. blades" business models. 3D printers exist that are seemingly cheap, but which require proprietary filament cartridges, where the consumable filament costs two to three times the going market rates.

Moving to kits, both the Printbot and Ultimaker are examples of printers that arrive as kits to be assembled by the end user. Both feature great instructions, and assembly is focused on mechanical construction, since both include all electronics pre-soldered and ready to go.

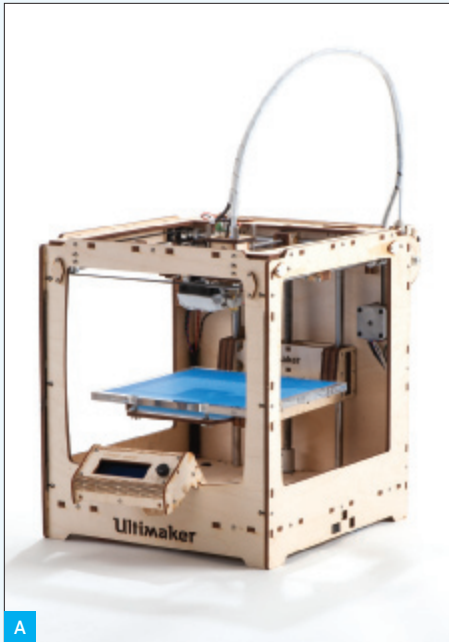
If you're interested in the full DIY experi-

ence, both the RepRap printers and the Rostock are entirely DIY. Both printers are composed of a combination of 3D-printed parts and various metal or wood bits, along with some electronics. You can order pre-printed parts kits from a variety of sources (eBay included). Electronics and/or mechanical packs are available, too. Generally, the more cutting-edge the printer version, the more parts you'll need to source.

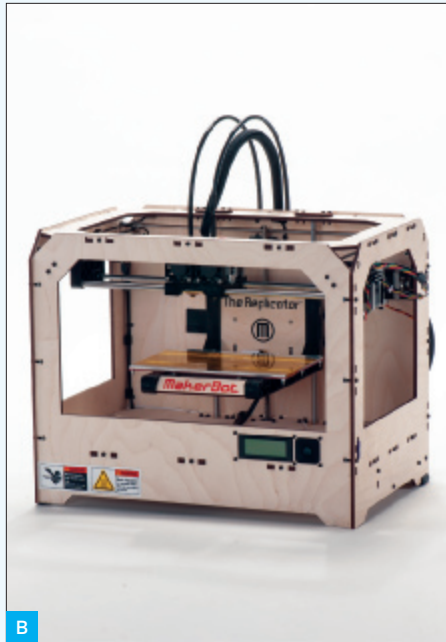
On pages 14–15, you'll find an overview of 3D printer anatomy, breaking down positioning systems, parts, and filament.

SOFTWARE

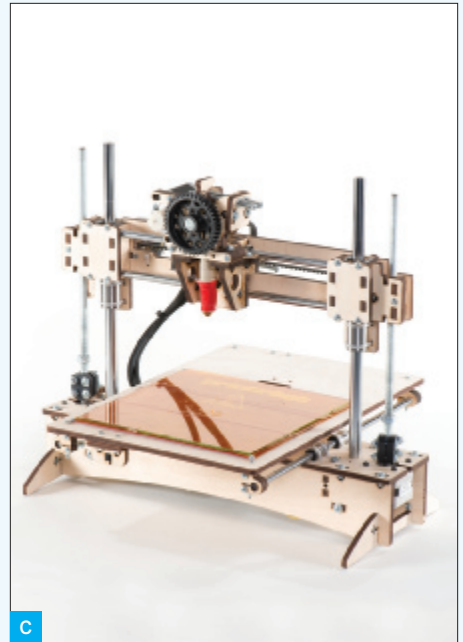
The workflow for turning an idea into a



A



B



C

3D POSITIONING SYSTEM

Within the build volume, the printer must be able to position the hot-end at any point to be able to precisely extrude material within the layer being printed. However, motion doesn't have to be limited to the hot-end.

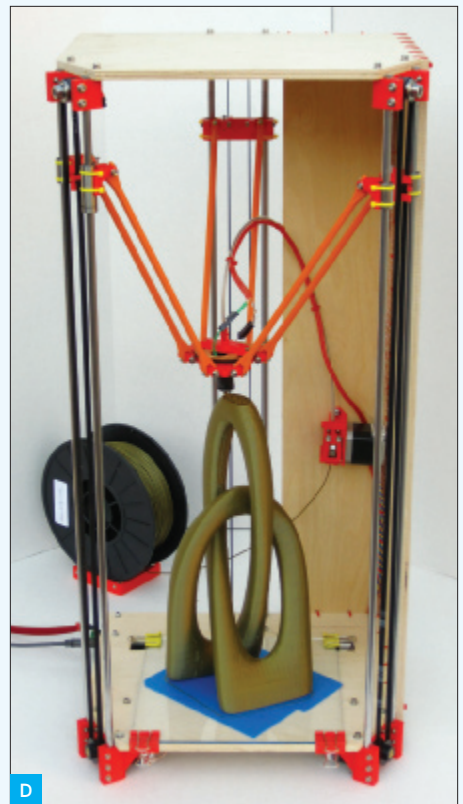
3D printers may move the hot-end or the print bed in a number of different ways. Here are three primary designs in use today.

GANTRY This style of printer moves the extruder in the x- and y-axes, while the bed moves only in the z-axis. Both the Ultimaker (Figure A) and the MakerBot Replicator (Figure B) use a gantry to move the extruder. However, the similarity ends there. The Replicator integrates the extruder with the hot-end. The Ultimaker uses a Bowden cable to separate the two. The Replicator has a simpler design, whereas the Ultimaker greatly decreases the weight of the print head, allowing for greater print speeds (at the cost of additional maintenance issues).

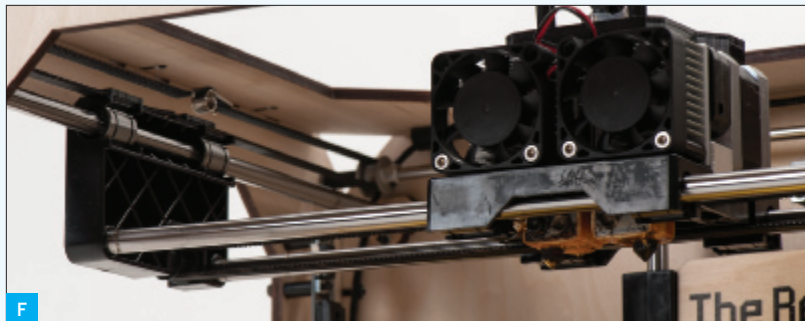
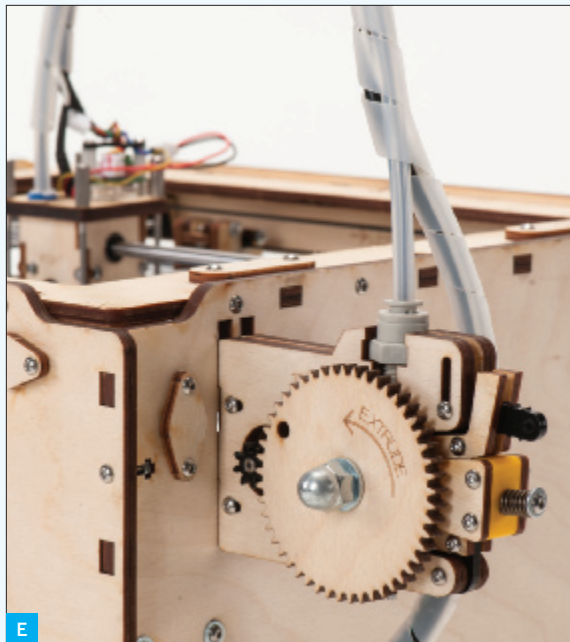
MOVING BED Instead of moving the print head in x-y, one of the axes is changed by moving the print bed itself. Usually, a moving-bed printer will move the print head in the z-axis. This is a mechanically simpler design in that the x- and y-axis are managed independently using entirely linear motion. It has the disadvantage of requiring the printer to move a significantly heavier print bed, which could knock loose the printed part. Slower, but simpler. Printrbot's models (Figure C) are examples of moving-bed printers that trade print speed for low cost and ease of maintenance.

DELTABOT Industrial pick-and-place robots typically use this design. A deltabot has three control rods connected to the toolhead, and these rods can be moved to control the position of the head. Recently, Johann Rocholl adapted this technology to 3D printing and created the Rostock (Figure D). Hard to explain, it looks like an alien probe is printing your favorite model.

The Rostock printers (so far) use a Bowden setup to separate the hot-end from the extruder, allowing for very quick and precise head positioning with relative mechanical simplicity. The downside is increased complexity in the driver; the hot-end positioning is not a linear set of steps because of the non-linearity of the motion between the vertical axis and the planar positioning of the hot-end.



D



With that in mind, the three most common materials are PLA, ABS, and PVA. (Read more about materials choices on page 22 and 24–25.)

ABS (ACRYLONITRILE BUTADIENE STYRENE), the cheapest of the three, is typically extruded at between 215°C–250°C, and does best with a heated bed to prevent warping. ABS creates mild, generally tolerable fumes that may be dangerous to sensitive people or certain pets (personally: fume hood, please!). ABS can be quite versatile. It can be sanded, and by mixing ABS with acetone, it can be easily glued together or smoothed to a glass-like finish.

PLA (POLYLACTIC ACID OR POLYLACTIDE) is a biodegradable plastic typically made from corn or potatoes. PLA filament is extruded at a lower temperature of 160°C–220°C and does not require a heated bed (painter's tape is just fine). When heated, PLA smells a bit like sweet, toasted corn. PLA tends to be stiffer than ABS. While PLA does not require a heated bed, it can warp a bit during cooling, something that a heated bed can greatly improve. Note that there is a "flexible PLA" variant that, while trickier to use, will result in objects that are squishy.

PVA (POLYVINYL ALCOHOL) is a specialty plastic used on multiple-extruder printers to print support material. PVA is typically extruded at 190°C, is water soluble, and can be used to print support material in complex 3D prints with lots of overhangs. PVA absorbs water like a sponge, which can make for extremely problematic use in high-humidity environments.

ALTERNATIVE MATERIALS While MPD printers are generally tuned to filament printing, it's not hard to adapt them to support other materials. A common mod is to add a syringe-style extruder that can handle materials from chocolate to frosting to various kinds of clays.

3D PRINTER PARTS

PRINT BED This is the bed upon which the printed part rests during production. Bed temperatures can be ambient or heated. A non-heated bed is often covered in painter's tape, as seen in the Ultimaker (Figure A), to which the printed material adheres. Heated beds, as seen in the Printbot (Figure C), keep the part warm during the print and prevent warping. Depending on material, a heated bed will maintain a temperature from 40°C to 110°C throughout the print. Let it be noted that the insides of a 3D printer are not a finger-friendly zone (and I have the blisters to prove it!)

EXTRUDER The extruder is not actually the part that squirts out plastic. The extruder is the part that feeds the plastic filament into the hot-end. Extruders may be integrated into the hot-end or they may be remote, typically pushing the filament through a stiff PTFE (Teflon) tube (this is the Bowden cable) into the hot-end (Figure E).

With a dual extruder (Figure F), you can print two different materials or colors simultaneously. This versatility comes at a cost of complexity (and price), as it requires an extra extruder, hot-end, and all the bits in between. Some printers, like the Ultimaker, can be upgraded from single to multiple extruders. Others cannot.

HOT-END The hot-end is comprised of a heater, a temperature sensor, and an extrusion end through which the plastic filament is pushed to deposit molten material (Figure G). Hot-ends are often assembled within an aluminum block or are configured in a barrel-type shape.

Note that the interface between the hot-end and the extruder – be it directly integrated or with a Bowden cable between the two – can be exceptionally problematic on some printers or on a printer that is not adjusted properly.

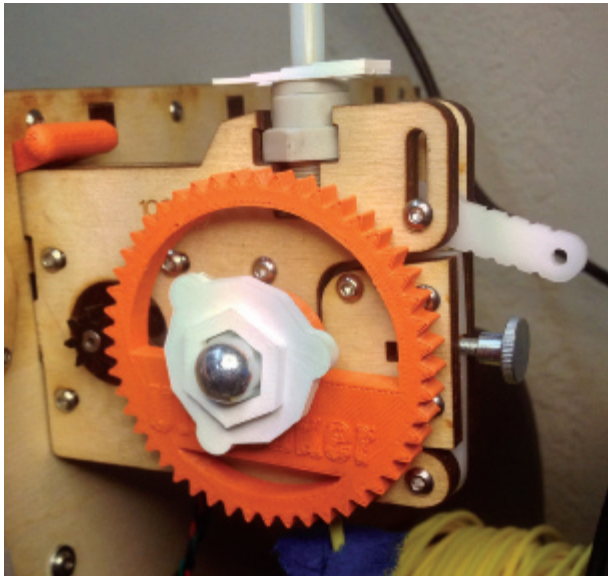
The hole in the nozzle may range in size, typically between 0.2mm and 0.8mm. The smaller the nozzle, the more detailed the print, but the longer it takes.

PLASTIC FILAMENT The filament is the consumable of the printer. Like an inkjet squirts ink, a 3D printer squirts melted filament.

CHOOSING FILAMENT

There are a handful of plastics that are compatible with MPD-based printers. Each has their pros and cons. Personally, I've chosen to print exclusively with PLA because of its low toxicity and general environmental friendliness.

Note that not all printers are compatible with all materials. Some materials may really stress a printer, as the temperature range for extrusion may vary from 160°C to 305°C, depending on material. A printer designed for PLA/ABS at a max of 250°C may fail entirely at 300°C.



Five 3D-printed replacement parts for my Ultimaker: a new drive gear, the white knob holding the gear on, the Bowden tube clamp (the white piece at the top of the extruder assembly), the orange piece on the left that holds the extruder in place, and a filament spool holder (hidden).

is Thingiverse (thingiverse.com), where you can find thousands of printable solutions for everyday problems: phone cradles, earbud holders, silverware dividers, quadcopters (yes, printable quadros), camera parts, game pieces, printable 3D printers, etc. You name it, there are likely at least a few good starting points on Thingiverse.

» **Slice** The *slicer* is what turns an STL file into a series of commands — typically G-code — that tell the printer where to move the print head and when to extrude plastic. While the printer's driver software is dictated by the printer, it's actually a critical piece, as the printer software will often model the motion dictated by the stream of commands and will vary the acceleration of the motors to eliminate print artifacts.

Slicing is a critical phase of the print. It's a careful balance between quality, speed, and amount of material used. In many cases, the choice of appropriate slicing parameters is the difference between a successful print and a pile of spaghetti.

» **Fixup** During *fixup*, the STL to be printed is often checked for errors (modelers sometimes dump 3D descriptions that look OK, but can't translate directly to a 3D print because the structure is invalid). The model may be rotated or scaled, or it may be duplicated to print multiple copies simultaneously. Often, slicing and fixup are contained in the same program (sometimes with the printer driver, too). Cura (wiki.ultimaker.com/cura) and Slic3r (slic3r.org) combine slicing with limited fixup, offering the ability

to rotate, scale, and print multiple different STL files in a single print run. Netfabb (netfabb.com), a commercial package, has extensive mesh debugging and fixup capabilities, along with basic layout tools and a powerful slicer (see [page 98](#)).

YOUR FIRST PRINT JOB

Now that you have a background on all things 3D printing and have bought or built your first 3D printer, how do you go about creating useful things (or creating useless, but very cool, things)?

The first step is to know your tools. If applicable, download and print all of the upgrades and replacement parts for your printer. For the Ultimaker, I've printed a number of parts, some of which can be seen in the image above.

Then download and print some useful things from Thingiverse. Start with small items — but not too small — like an earbud holder, bottle opener, or a simple character. Choose something where lots of folks have uploaded photos of their own versions (under the "Who's Made It?" section). By starting with a known, working model with lots of examples, you can compare your product to others and will have a much better basis for fixing any problems and tuning your workflow (likely the slicer, in particular) to maximize print quality from your printer.

Each type of 3D printer has a particular sound of a successful print. Learning it can help you identify problems before they become serious. I can be in a different room

and still tell when a print on my Ultimaker is about to fail just because it starts to sound out of whack.

Have a look at how various models are constructed. The key challenge in creating a 3D model is how the desired real-world object can be broken down into a series of commands — "draw a line and a curve," "extrude this surface," "fillet that corner," "cut a hole here" — that you can use to create the object. If you can find some models on Thingiverse that are in a file format you can edit, try your hand at editing them to see if you can add a feature you desire.

Once you're ready to start from scratch, the first tool you'll need is a set of calipers. Digital slide calipers with 0.01mm accuracy can be had for less than \$20. Try creating hangers or hooks that require a precise measurement to fit snugly on an already-existing object (like over a door), giving both a feel for using the calipers and helping you dial in how your printer maintains dimensions throughout the printing process.

One unique challenge is learning to think in a 3D-printer-compatible way. As mentioned, objects with structures that tilt at more than 45° can't be printed without support material because the object will sag. Note that bridges — linear spans of plastic over a gap — work surprisingly well, but print them so the first layer of the bridge is on the inside of an object and won't be seen.

While you can turn on "support material" in most slicers, doing so often causes a lot of extra material to be used, which is both wasteful and requires a ton of post-print cleanup. Note that, with a dual extruder printer, you can print PLA or ABS on one extruder while printing with water-soluble PVA on the other extruder, making cleanup a simple matter of soaking the piece in a bucket overnight.

There is also a balance between creating walls that are too thin and too thick. Thin walls can lend elegance to an object, but print too thin and that single or double layer of linear plastic filament will fail quickly. Naturally, this all becomes more intuitive with practice and experience.

Bill Bumgarner (friday.com/bbum) plays with high voltage, cooks with fire and water, incubates microbes, hacks code, corrals bugs with his son, and tries to make stuff do things that were never intended.

NEXT STEPS: WHAT TO MAKE

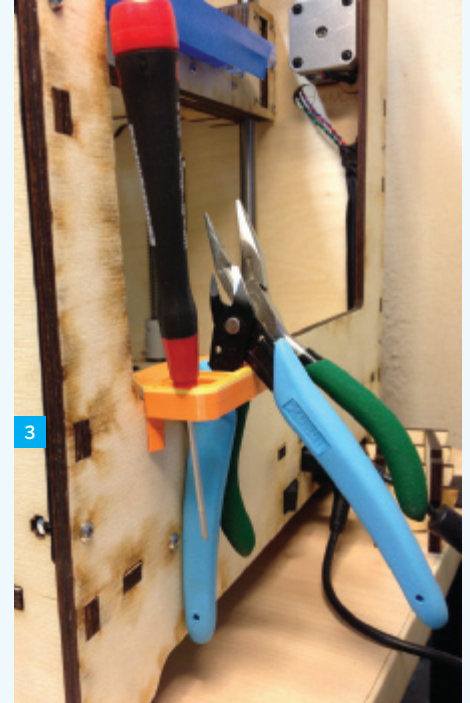
Once you start to get the hang of 3D printing, a world of possibilities opens up. I've given many of these things away as gifts. The material costs are very cheap and the look of surprise when you say, "Yeah, I printed that. You want it? Different color? Nah, no problem, I can print as many as you want easily," is priceless! With my Ultimaker, I have printed the following handy bits, and many, many more.



1



2



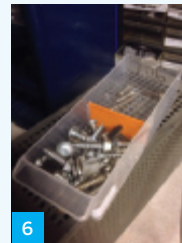
3



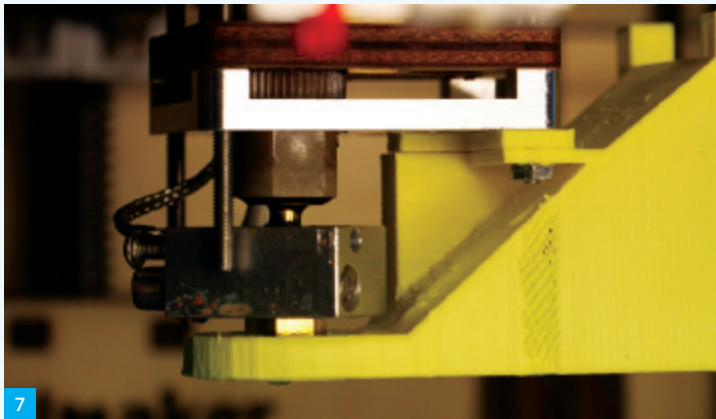
4



5



6



7



8

1. Replacement screw cap for a large bottle of Jack Daniels (thingiverse.com/thing:18194)
2. Case for a Teensy-based IR Blaster (thingiverse.com/thing:19315)
3. Ultimaker tool holder (thingiverse.com/thing:18098)
4. Nautilus-shaped earrings (thingiverse.com/thing:13450)

5. Aeroponic grow pods for a winter herb/salad garden (thingiverse.com/thing:32613)
6. Drawer divider for my son's screw sorting efforts (thingiverse.com/thing:32614)
7. Fan shroud with spacer (thingiverse.com/thing:16530)
8. Raspberry Pi case (thingiverse.com/thing:25363)

Not shown:

- » Flashlight wall mounts
- » Fixes for our shower (rod caps and washcloth holders)
- » iPad stand and iPhone stand customized to application
- » Klein Bottle Opener ([page 13](#))
- » Multiple octopodes
- » Earbud holders
- » Razor scraper

- » Wii sensor bar mounts custom-fit to the top of our TV
- » 3D models from a friend's video game he built in school
- » Multiple items to fix doors and switches in a friend's house
- » Bottoms for our soap dispensers so they don't stain the counter with rust
- » Feeder for our parakeet, Steve

- » Alien-faced tops for our lava lamp collection
- » Various Ultimaker upgrade parts on the extruder: gear, nut handle, extruder lock, Bowden lock, feet

COMPILED
BY
GARETH
BRANWYN

Octopod Underwater Salvage Vehicle

Sean Charlesworth

Until we can afford an amphibious car this model is the next best thing.

opus5.complex88.com

+ Interviewed by MAKE: makezine.com/go/octopod

InMoov Robotic Arm

"Hairygael"

This is not a toy. The functionality of this arm is impressive.

thingiverse.com/hairygael

+ letsmakerobots.com/node/31978

100

Coollest 3D-Printed OBJECTS

Clutch: Printable Purse

Kacie Hultgren

This purse is as cool as it is compact.

thingiverse.com/thing:31234

6-Stage Planetary Gear Set

Richard Horne aka "RichRap"

Planetary gears exemplify the complexity you can achieve with 3D-printed objects and this set is a gem.

thingiverse.com/thing:25769





McCormick D326 Tractor

Juan Esteban Paz
The detail on this model is amazing.
thingiverse.com/thing:29869



Crania Anatomica Filigre

Joshua Harker
If there's a cooler 3D-printed object than this we're not aware of it.
joshharker.com



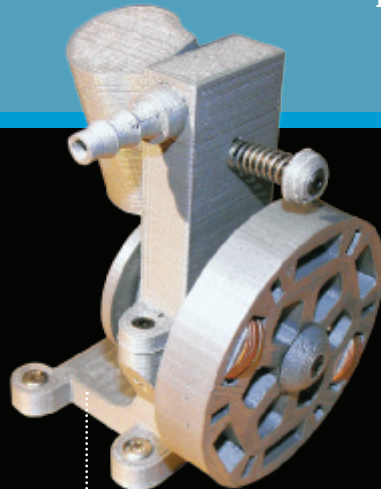
Puddle Jumper Whirligig

"23Meteor"
Print, glue, snap, spin, and watch it fly.
thingiverse.com/thing:22454



Sue: The Model T. Rex

Mike Mocer
Who needs Toys "R" Us when you can print your own dinosaurs?
thingiverse.com/thing:25779



Working Oscillating Steam Engine

Charles Babbage
Not quite steampunk. How about steam plastic?
thingiverse.com/thing:25624

3D-Printed Bikini

Mary Haug and Jenna Fizel
Looks cool, but not sure how cool it would feel on a hot day at the beach.
shapeways.com/n12_bikini
[+ continuumfashion.com](http://continuumfashion.com)



Desk Lamp

MakerBot Industries
Just snap this together, add a bulb and a power source, and you've got light.
thingiverse.com/thing:27062



Giant Keys Baby Toy

Nirav Patel
Print usable house key duplicates for your visiting guests. Or scale the key model up 200% and you've got a classic baby toy – giant plastic keys! Another fun infant toy: Roll-A-Hedgehog.
thingiverse.com/thing:8925, thingiverse.com/thing:27487



COMPILED
BY
**STETT
HOLBROOK**

10

Most Useful 3D-Printed OBJECTS



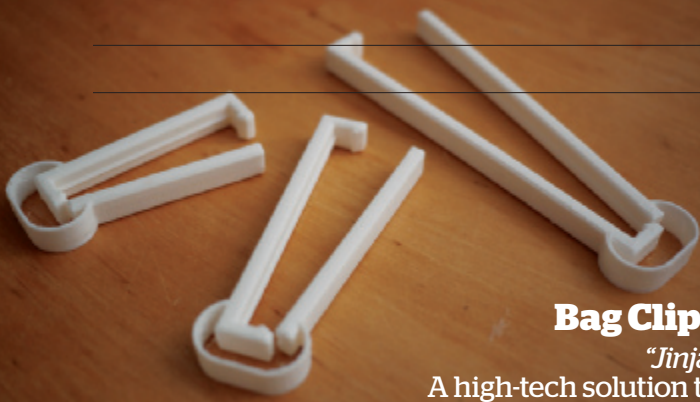
Coin Sorting Tray

Xander Brown
Stack them and shake them to sort.
thingiverse.com/thing:30631

AA-to-C Battery Adapter

"Zero_o"
If your device calls for a C battery and all you've got is a AA, print out this adapter and you're back in business.
thingiverse.com/thing:8226





Bag Clips

"Jinja"

A high-tech solution to a low-tech problem: stale chips.

thingiverse.com/thing:30664

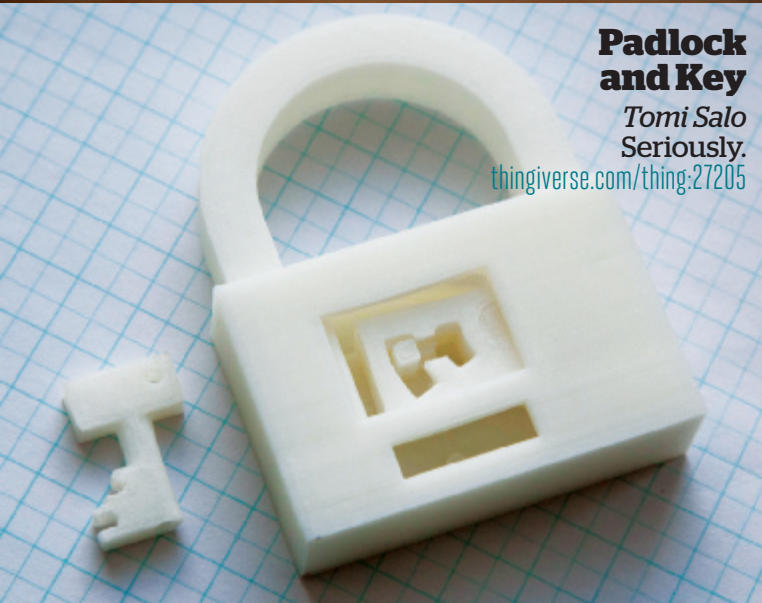


Watering Can Spout

Mark Edmondson

Broken watering can spout? Print one that's built to last, with $\frac{1}{8}$ " walls. You can't buy that at the store.

thingiverse.com/thing:9535



Padlock and Key

Tomi Salo
Seriously.

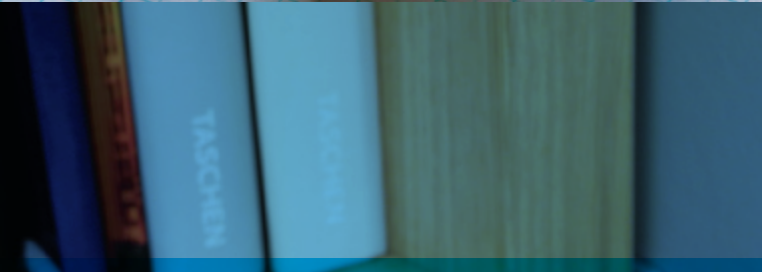
thingiverse.com/thing:27205

Joystick

Mark Dufour

Keep the joy alive with a new joystick.

thingiverse.com/thing:30008



Desktop Network Socket

Ralph Bolton,

Perfect for connecting your 3D printer to your computer.

thingiverse.com/thing:30574

13:30 Printable Headphones

John Mabry

Because everybody loses their headphones.

thingiverse.com/image:31392

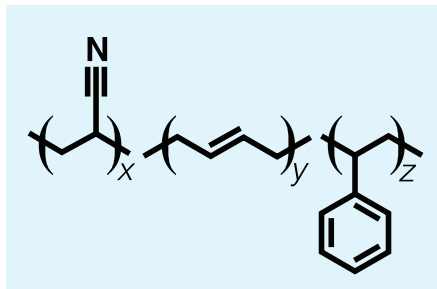


PLASTICS FOR 3D PRINTING

WRITTEN
BY
SEAN
RAGAN

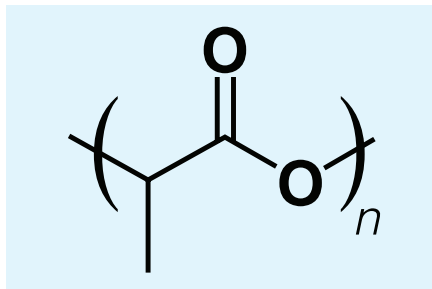
Not all filament is created equal. From rigid to rubbery, water-soluble to solvent-proof, here's the skinny on the stringy stuff.

ACRYLONITRILE BUTADIENE STYRENE (ABS)



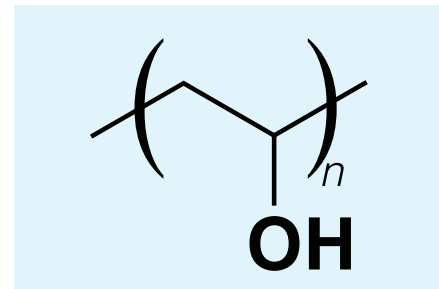
- » **NOZZLE TEMP:** 215-250°C
- » **BED TEMP:** 90-103°C
- » **PRINT SURFACE:** Kapton tape
- » **ENVIRONMENTAL FOOTPRINT:** Non-biodegradable, recycling code #9, not normally allowed in mixed recycling streams
- » **NOTES:** Plastic used in Lego elements. Most popular choice for 3D printing.

POLYLACTIC ACID (PLA)



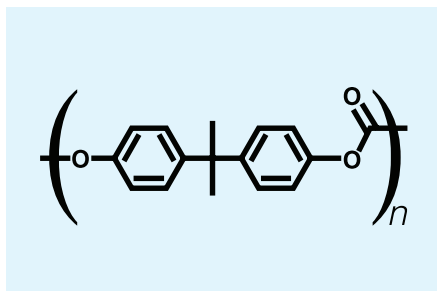
- » **NOZZLE TEMP:** 160-220°C
- » **BED TEMP:** Ambient to 60°C
- » **PRINT SURFACE:** Blue painter's tape
- » **ENVIRONMENTAL FOOTPRINT:** Biodegradable, recycling code #7, may cause problems in mixed recycling streams
- » **NOTES:** Available in hard and soft grades. Gaining popularity fast, may overtake ABS in the near future.

POLYVINYL ALCOHOL (PVA)



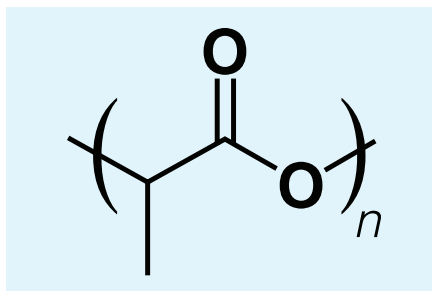
- » **NOZZLE TEMP:** 180-200°C
- » **BED TEMP:** 50°C
- » **PRINT SURFACE:** Blue painter's tape
- » **ENVIRONMENTAL FOOTPRINT:** Biodegradable, water soluble
- » **NOTES:** Used as dissolvable support material or for special applications. Likely to see more use as multi-head printers proliferate.

POLYCARBONATE (PC)



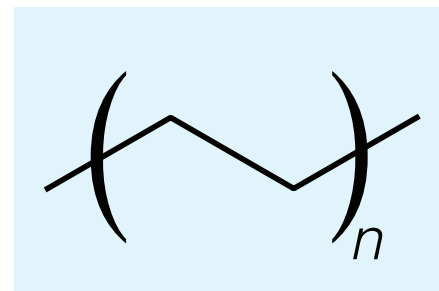
- » **NOZZLE TEMP:** 280-305°C
- » **BED TEMP:** 85°-95°C
- » **PRINT SURFACE:** Kapton tape
- » **ENVIRONMENTAL FOOTPRINT:** Non-biodegradable, recycling code #7
- » **NOTES:** Requires high-temperature nozzle design. Proof-of-concept stage.

POLYLACTIC ACID (SOFT PLA)



- » **NOZZLE TEMP:** 200-220°C
- » **BED TEMP:** Ambient
- » **PRINT SURFACE:** Glass plate
- » **ENVIRONMENTAL FOOTPRINT:** Biodegradable, recycling code #7, may cause problems in mixed recycling streams
- » **NOTES:** Flexible/rubbery, limited colors, and limited sources. Likely to get easier to find as 3D printing spreads.

HIGH-DENSITY POLY- ETHYLENE (HDPE)



- » **NOZZLE TEMP:** 225-230°C
- » **BED TEMP:** Ambient
- » **PRINT SURFACE:** Polypropylene sheet
- » **ENVIRONMENTAL FOOTPRINT:** Non-biodegradable, recycling code #2, resists almost all solvents and glues
- » **NOTES:** Difficult to use due to shrink/warp/curling problems. Rarely used.

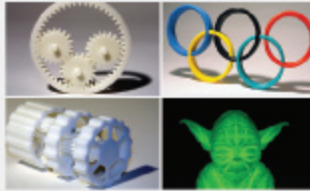
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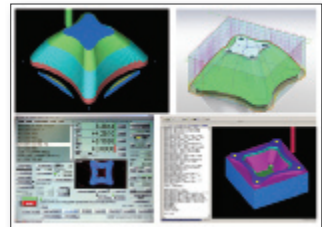


TORMACH MAKER PROFILE - BROOKLYN CUSTOM

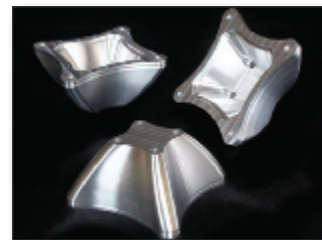
Brooklyn Custom Metal Fabrication specializes in custom fabrication for architects, artists, and designers, with installations.

Over the last decade, owner David Stanavich has built a portfolio of high-end custom metal drawer pulls, knobs, and architectural hardware for a diverse commercial and residential clientele. Digital design and CNC fabrication techniques are essential to his products.

"What drew me to Tormach was the affordability of the PCNC mills," relates Stanavich. On the importance of the PCNC 1100 to his business: "What's happening now is that I'm making the shift from a contract fabricator who has never done the same job twice to small-run production work that I am designing."



CAD CAM and Controller software programming examples for a CNC machined prototype part.



Stanavich is also using his PCNC 1100 to machine the permanent molds for toys he uses as unique calling cards for the shop.

Read the full story at: www.tormach.com/brooklyn

WRITTEN
BY
STUART
DEUTSCH

BEYOND THE EXTRUDER

A guide to 3D printing materials and methods.

- ▶ **THERE HAS NEVER BEEN A BETTER TIME TO PURCHASE A DESKTOP 3D PRINTER.** Nonetheless, they are still too expensive for many users. If you can't justify the cost of a personal printer, you may be able to access one at a local hackerspace, and there are many online 3D printing services to choose from, including Ponoko, Shapeways, and i.materialise. These companies use a variety of printing technologies to create physical objects from your digital designs and can print in many other materials besides extruded thermoplastic.

Stuart Deutsch is a DIYer who writes a whole lot about tools at toolguyd.com.

» *Bowie the Bunny* in fine mineral powder, with color binders, via powder bed/inkjet process.

COMPOSITES & CERAMICS

POWDER BED AND INKJET HEAD PRINTERS use inkjet-type print heads to deposit tiny droplets of liquid binder on top of a thin layer of powder. Once the build platform lowers, a roller spreads and compacts a fresh layer of powder across the surface. The final object is essentially a stack of powder layers finely glued together. Dyed binders can be used in certain machines to produce full-color display models (above). Treatment with super glue and UV protectants can improve model strength and reduce color fading.

The powder bed/inkjet system can also be used to create food-safe ceramic models (right). The use of ceramic powder has become quite popular with online printers who now offer a rainbow of single-color options. After removal from the powder bed, raw ceramic parts undergo a series of heat treatments to dry, fire, and glaze the model, improving both strength and appearance.



« Food-safe ceramic, via powder bed/inkjet process, followed by heat treatment.

PLASTICS

STEREOLITHOGRAPHY (SLA) is the original 3D printing process, in which a liquid plastic resin is selectively hardened by exposure to high-intensity light, often from a laser. After the laser has drawn a 2D path along the surface, the freshly polymerized model layer is lowered into the surrounding resin bath. The laser traces over the fresh surface, curing and joining the resin to the previous layer. SLA produces prints of exceptional smoothness.



SELECTIVE LASER SINTERING (SLS) uses a high-power laser to melt and fuse particles of very fine plastic powder, often nylon. The laser scans across a leveled and compacted powder surface, and when each layer is completed, the entire bed is lowered and fresh powder is spread on top. As the laser works its way across the top surface fuse to each other and to the layer below. The unfused powder acts as support material, so SLS fabrication works well for models that have thin sections, overhangs, or complex geometries.

SLS is one of the most economical 3D printing methods and is forgiving in terms of design guidelines. Most vendors charge by volume of powder consumed, so you can often save money by “hollowing out” solid models and printing them as shells. Most vendors also charge for “trapped” powder, however, so models printed as shells will usually need to include at least one small hole so that the powder can be recovered when the print is done.

◀ Fused nylon powder, via selective laser sintering.



⚡ Bronze-infused stainless steel, via direct metal printing.



⚡ UV-curing acrylic, via photopolymer jetting.

PHOTOPOLYMER JETTING uses movable heads, like an inkjet printer, to deposit droplets of resin onto a build platform through a number of very small jets. Once the droplets are in position, a UV lamp moves across the platform to harden the resin. A support material may be printed surrounding the droplets and can be removed, manually or by washing, once the print is complete. Photopolymer jetting can create very finely detailed models with smooth surfaces and multiple materials – tinted, clear, rigid, flexible, etc. – in a single print. It is not widely available from 3D printing services, yet.

METALS

DIRECT METAL LASER SINTERING (DMLS) uses a laser to directly fuse certain metal powders, such as titanium, in a fashion very similar to SLS in plastics. Other specialty alloys can be printed via DMLS, but high costs and stricter design guidelines make the process less accessible to beginners.

DIRECT METAL PRINTING uses a multi-step method to create powder-based metallic models, mainly from stainless steel. First, the object is printed into a bed of very fine stainless steel powder using the inkjet-binder process. A carefully controlled heat treatment then burns out the plastic binder and fuses the steel particles together. Finally, the porous sintered model is infused with molten bronze, which

wicks into the empty spaces and fills them. The finished model is a kind of stainless steel sponge filled with bronze, and can be given a variety of surface treatments including plating with gold or other metals.

INDIRECT PRINTING METHODS create positive or negative models that can be used with conventional casting processes to create metal parts. For instance, a sacrificial model of a part can be 3D printed in a wax-like resin using stereolithography, and then duplicated in metal using the traditional lost-wax process. Alternately, the powder bed/inkjet process can be used to print molds in silica sand or other traditional foundry media, which are then used to cast metal parts in the normal way.

THE 3D PRINTING SOFTWARE TOOLCHAIN

An overview of the CAD, CAM, and client software you need.

WRITTEN
BY
MATT METS
AND
MATT
GRIFFIN

▶ YOU'VE GOT A SHINY NEW 3D PRINTER AND A BRILLIANT IDEA FOR YOUR FIRST ORIGINAL DESIGN — NOW WHAT?

Creating and printing your own unique 3D models requires three kinds of software. First, there's the 3D modeling program used to design the shape of your creation. Traditionally, the use of software to prototype physical objects has been referred to as *computer-aided design (CAD)*. Second, there's the *computer-aided manufacturing (CAM)* program (commonly referred to as a *slicer*) that converts your model into specific, mechanical instructions for the printer robot. Third, there's the *printer control software*, or *client*, that sends those instructions to the printer at the right time, and provides a real-time interface to the printer's functions and settings.

3D MODELING/CAD SOFTWARE

Probably the most important software choice you'll make is what kind of modeling program to use. There are many to choose from, but they fall into four basic types: *solid*, *sculpting*, *parametric*, and *polygonal*. Each type will help you turn your idea into reality, but one may be handier for, say, designing a mechanical part, and another for sculpting an action figure.

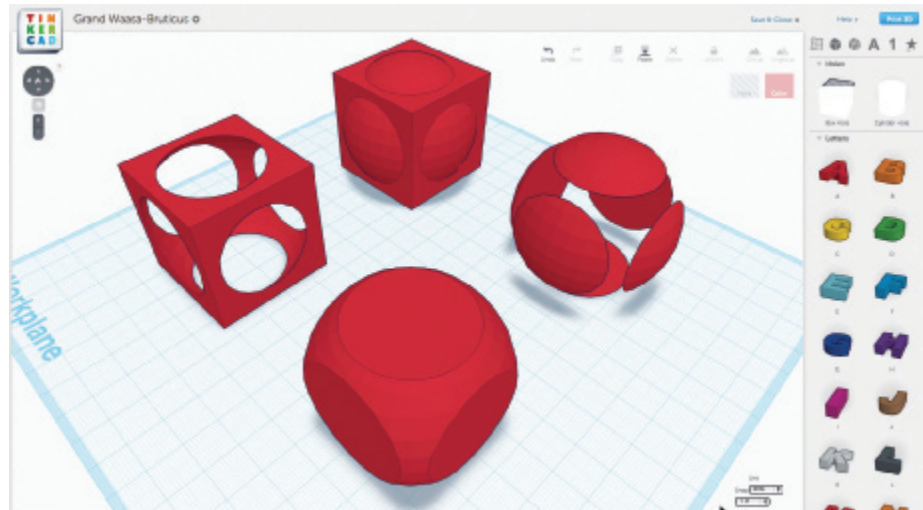
Solid modeling programs mainly use a method called constructive solid geometry (CSG), or similar techniques, to define complex 3D shapes. Popular free solid modeling programs include **SketchUp**, **Autodesk 123D**, and **Tinkercad** (which runs entirely in your web browser; read a tutorial on *page 30*). In a solid modeling program, simple "primitive"

BEGINNER-FRIENDLY OPTIONS:

CAD: **Tinkercad**

CAM: **Slic3r**

Client: **Pronterface**



Basic Boolean operations illustrated in Tinkercad. From back to front: union, two possible differences, and intersection of concentric cube and sphere.

shapes like boxes, cylinders, and pyramids are manipulated to make more complex shapes, often using Boolean operations. For instance, a hollow box can be modeled by drawing two overlapping cubes, one slightly smaller than the other, and “subtracting” the smaller from the larger.

Solid modeling programs have three big advantages. First, the solid modeling design process tends to be more intuitive than other methods, and is often the easiest way for beginners to get started. Second, the interface usually makes it easy to set precise measurements between objects, which is handy for creating mechanical parts. Third, the software handles most issues of manifold integrity (“water-tightness”) for the user automatically, despite the very large number of operations that may go into shaping a complex form.

Sculpting modeling programs, such as **ZBrush**, **Sculptris**, and **Mudbox** use a more freeform interface to slice, tug, twist, and press the surface of a “blob” into the desired shape. This makes them great for forming organic surfaces such as faces or figures, but less suitable for precise parts or flat surfaces. A great tool to start with is **Sculptris**, little brother of the more expensive **ZBrush**. (Many polygonal modeler applications such as **Blender**, **Modo**, and **Maya** are beginning to offer built-in sculpting tools as well.)

Parametric modeling programs, such as **OpenSCAD**, are fairly unique; instead of drawing shapes using a mouse, objects are modeled by writing simple programs that describe how to combine different shapes



« Nervous System’s “Convolution” bangle, stainless steel, based on simulated forces in a cellular network.

» Pixologic’s **Sculptris** allows you to sculpt 3D models like blobs of clay. Tooltips have names like *crease*, *inflate*, *smooth*, *pinch*, and *flatten*.



together. Because each dimension can be specified precisely, this kind of tool is great for quickly creating things such as technical parts like enclosures, gears, and other mechanical objects.

On the other hand, parametric modelers are also useful for producing generative artwork. Tools such as Marius Watz’s **ModelBuilder** and the **Grasshopper** editor for **Rhino** are geared toward generating unexpected, abstract forms by processing other objects or data, or by pure math. Designers like Nervous System use them to create complex organic shapes that would be practically impossible to model by hand.

Polygonal modeling programs represent objects using thousands of tiny triangles arrayed together in a mesh that defines

model surfaces. Notable examples include **Blender**, **3ds Max**, **Maya**, and **Modo**. They're great for 3D graphics and animation, but require a bit of care when used for 3D printing to make sure that meshes remain manifold or water-tight, i.e. without missing polygons or disconnected vertices. If a model is not manifold, the slicer may not be able to tell its inside from its outside, and may refuse to process the model at all, or may produce G-code containing serious errors.

Polygonal modeling programs offer a tremendous amount of control, but are often challenging to learn. Effective mesh modeling

requires mastering a number of sometimes counterintuitive principles like working with "quads" (instead of triangles or "n-gons"), developing "edge-flow" to quickly manipulate models with operations like edge-cutting and loop-cutting, and using "subdivision" tools to automatically smooth jagged surfaces into more organic forms. Extensive tutorials covering these topics in most of the major programs can be found online. Watching a few videos demonstrating best practices, early on, can save a lot of trouble as your skills develop.

Your CAD program will produce a 3D

model in some file format, commonly STL. Depending on what software was used to produce it and how complex it is, your STL file may contain errors, such as holes or reversed normals, that will need to be corrected before it will print correctly. Your CAM software may detect these errors automatically, and some CAM packages, notably **Slic3r**, include repair routines that will try to automatically fix simple errors, but you cannot always rely on these to produce reasonable toolpaths. Models can also be repaired manually using a polygonal modeler. Another option is **MeshLab**, an advanced, open source STL processing and editing tool that is very powerful, but may be intimidating to beginners.

As you become more experienced with 3D printing, you might want to consider investing in a commercial STL analysis and repair tool such as **Netfabb Studio**. While their Basic suite works well for solving manifold issues quickly and effectively, the Professional version allows you to target specific elements of the model for manipulation, decimation, and re-meshing, as well as offering stable Boolean operations to split up a model into multiple parts. The Professional package also offers built-in slicing utilities and drivers for operating some of the printers directly, in some cases entirely replacing the CAM/client pipeline.

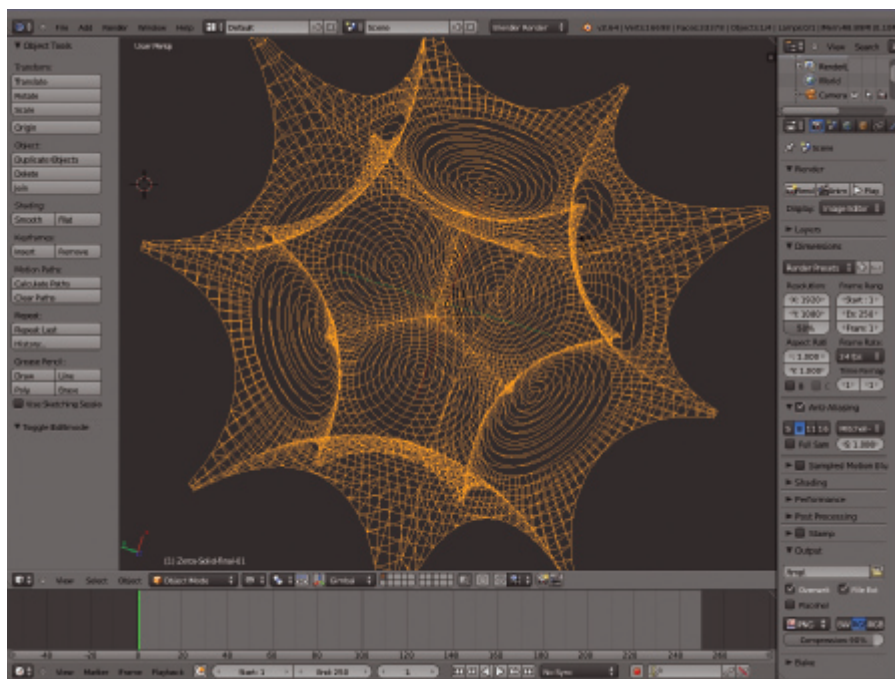
SLICING/CAM SOFTWARE

Once you have a manifold, error-free 3D model, it must be converted into specific toolpath instructions that tell the printer where to move the hot end, when to move it, and whether or not to extrude plastic along the way. This process is sometimes referred to as *skeining* or *slicing*. The standard format for these instructions is a simple programming language called G-code.

Historically, most printers have relied on the open source **Skeinforge** engine for preparing G-code from model files. Recently, however, alternative slicing programs have started appearing, most notably **Slic3r**, which has been slowly overtaking Skeinforge as the tool of choice.

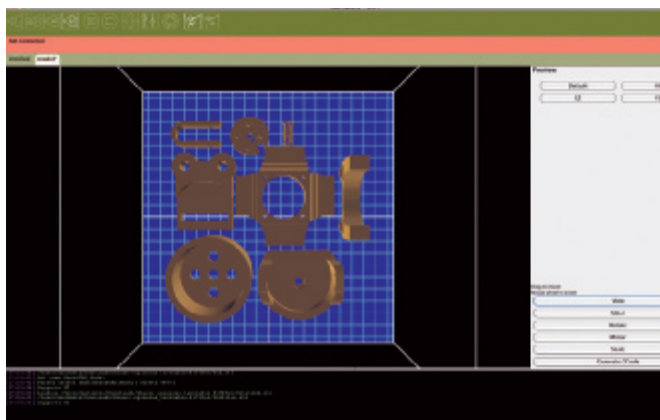
A fairly recent closed-source utility called **KISSlicer**, available in free and pro versions, boasts some unique features, such as adaptive sparse infill (using more material near the edges of a print and less in the center) and multi-extruder support (using different

One type of modeling program may be handier for, say, designing a mechanical part, and another for sculpting an action figure.



Blender is a free, open source polygonal 3D modeling program that is extremely powerful, but challenging to learn.

Laying out a build plate in ReplicatorG. All of these parts will print simultaneously.



material for separate models, support structures, and infill).

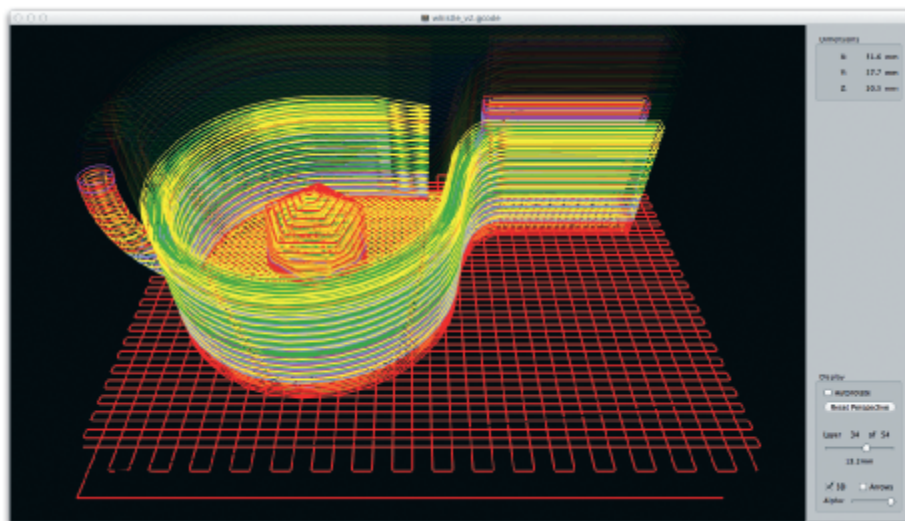
Finally, there's the new open source slicing engine from MakerBot called **Miracle-Grue**. As of this writing, it's still a work-in-progress, and not yet as mature as Slic3r. It can be tricky to set up as a freestanding application, but for coders it's really fun to play with.

Though most slicing engines can be run as standalone programs, they're commonly built into integrated printer client packages like **ReplicatorG** and **Pronterface**, so that the same interface used to control the printer can also be used to load and slice 3D models directly.

Note that, because a 3D print proceeds layer-by-layer, the G-code to print a single copy of a model is very different from the G-code to print, say, four copies side-by-side. If you want to print multiple parts per job, one option is to simply lay out build plates, as they're called, directly in your 3D modeling program. Another option, which many find more convenient, is to lay out build plates at the CAM level. Many slicing engines, as well as integrated print environments like ReplicatorG, now provide tools that allow easy scaling, repositioning, and duplicating of CAD models before slicing. These usually include a virtual environment that shows how everything will fit into the printer's build chamber.

The slicing program will provide an interface to adjust a number of variables related to print speed and quality, such as layer height, maximum print-head speed, infill density, number of "shells" surrounding the infill in each layer, and whether or not to print support structures or "rafts." Many slicing engines have built-in profiles to get you started, and most work well right out of the box. Eventually, you'll probably want to experiment with these settings to suit specific geometry or design challenges.

A handy practice when getting familiar with slicer settings is to use a *G-code visualizer* to preview the print. A visualizer will display the G-code commands as a series of lines to represent the print-head toolpaths. Scrolling through the layers can help you learn how the slicing software tackles the geometry of the original object, and will reveal errors without using up any plastic. Saving a series of G-code "drafts" of a figure before actually running a print job is a great



↗ Visualizing G-code in Pleasant3D. The interface allows you to scroll through the toolpaths one layer at a time.

way to gauge the effect of adjustments to the various slicer settings. If you're using ReplicatorG, grab **Pleasant 3D** (Mac) or **GCode Viewer** for Blender (cross-platform). Both Pronterface and **Repetier-Host** have built-in G-code viewing utilities.

PRINTER CONTROL/CLIENT SOFTWARE

Finally, there's the *client*, which is basically the printer's real-time control panel. It provides a software interface where you can start, stop, or pause the printing process at will, as well as set the temperature of the extruder nozzle and the bed heater, if present. The client will usually provide a set of directional buttons that allow you to incrementally move the print head in any direction, which can be useful for bed leveling, calibration, and manual zeroing.

Historically, most machines relied on ReplicatorG for machine control. Recently, though, some alternatives have appeared, and the amount of innovation is impressive. The **Printrun** suite (featuring Pronterface) and Repetier-Host are the most actively developed and used. Some closed-source printers, such as PP3DP's Up, ship with custom client software that will usually include a similar set of features.

In use, the essential function of the client is to send toolpath instructions to the printer over a wi-fi or USB connection. Many printers are designed for operation in "untethered" mode, in which the printer runs on its own without a computer connection.

In untethered mode, no client program is necessary; the printer automatically reads and follows CAM instructions from an SD card or USB thumb drive plugged into it directly. Untethered printing can be useful, for instance, for long-running prints during which you may want to use your computer elsewhere, or if you have more printers than computers to run them. CAM information is usually stored on removable media as G-code instructions.

WHAT NEXT?

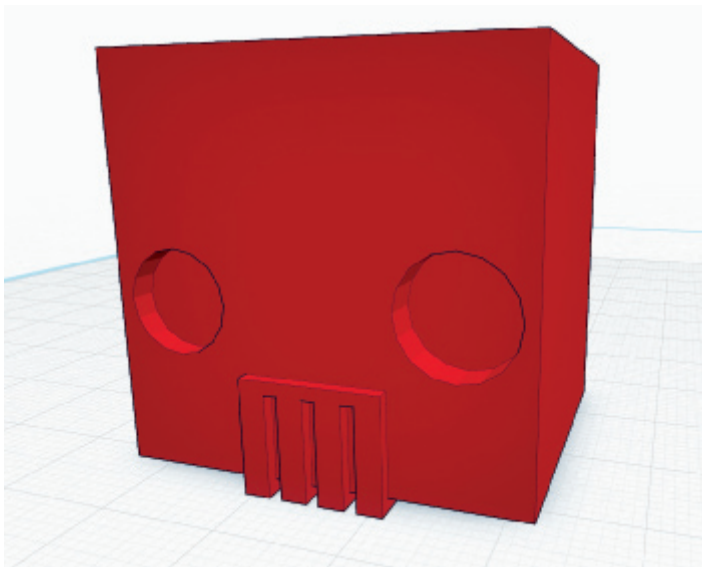
Your printed object will inspire improvements and new ideas. The design pipeline is really a cycle.

Now that you've got the basic workflow down, you're ready to make anything! Remember that 3D design and printing is an iterative process, and that things rarely turn out perfectly the first time around. If you aren't comfortable with any of the tools that you tried, be sure to look at others — there's no reason to limit yourself to only one workflow. Experiment, tweak, observe, repeat! Try to learn something from each mistake, and always remember to have fun.

Matt Mets is a maker who uses electronics to create playful objects that teach and inspire. Matt Griffin is the former community manager at MakerBot, and is currently director of community support and evangelism at Adafruit. He is writing a MAKE book on design for 3D printing.

3D DESIGN

for the COMPLETE BEGINNER



Use Tinkercad to design a robot-head pencil topper in minutes.

WRITTEN
BY
BLAKE
MALOOF

UNDERSTANDING POSITIVE & NEGATIVE SPACE

To utilize Tinkercad to its full potential you need to understand the concepts of positive and negative space. For example, you can place a box, which represents a solid, positive shape, and you can also place a hole, a negative shape. Holes remove any solid material within their shape.

This will become very important when you submit your model for printing. Because the cost depends on the solid volume of the print, you'll want to make the object as hollow as you can.

▶ **THREE-DIMENSIONAL PRINTING OFFERS EXCITING APPLICATIONS, FROM ART TO PRODUCT DESIGN TO ROLLING YOUR OWN REPLACEMENT PARTS.** But if you're new to this technology, the modeling software and printer hardware can be intimidating. The learning curve is steep as you go from concept to 3D model to printed object. If only you could create a simple design on your desktop, have it printed on a high-end 3D printer, and delivered to your door. Turns out, you can!

Tinkercad is an intuitive, browser-based CAD modeling application that allows you to quickly box out your design and hit a Print button to send it off to 3D printing services like Shapeways or Sculpteo. You can go from concept to ready-to-print 3D model in minutes with little to no modeling experience.

To get you started and to show just how easy it is to make something fun and unique, I'll walk you through the process for creating a robot-head pencil topper. All you need is a computer with an internet connection.

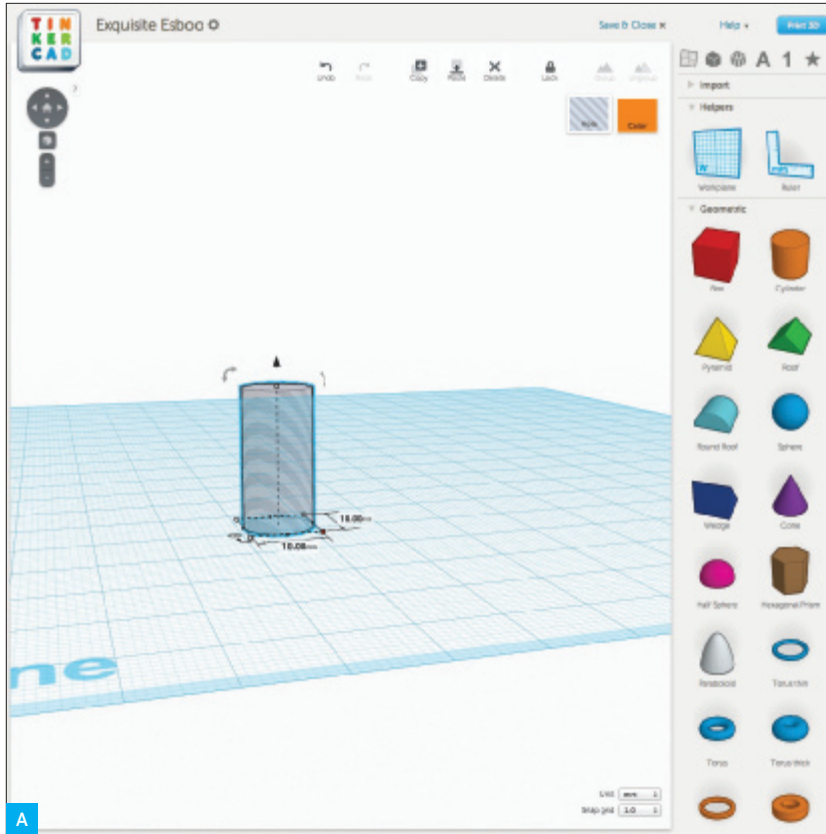
1. CREATE A TINKERCAD ACCOUNT

Tinkercad costs \$10 a month, but you can sign up for a 15-day free trial at tinkercad.com. Then click the Design a New Thing button. Tinkercad will give your new thing a name; change it by clicking the gear icon.

2. MAKE A HOLE

To make the hole that your pencil will fit into, measure the width and height of a pencil eraser. It's about 8mm at the widest, so click and drag a cylinder onto the Tinkercad "workplane" (the blue grid) and scale it to 10mm diameter. This will provide 1mm of wiggle room all around the pencil. To scale something in Tinkercad, first select it by clicking on it, then click on one of the small white rectangles situated around the object — these are called handles — and drag it. To scale the shape uniformly in all directions, hold the Shift key while dragging.

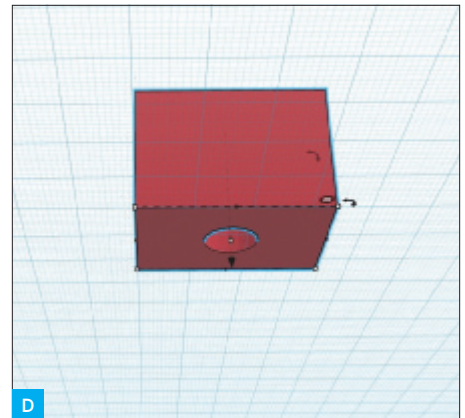
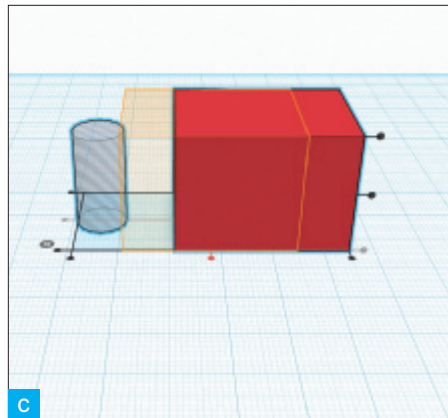
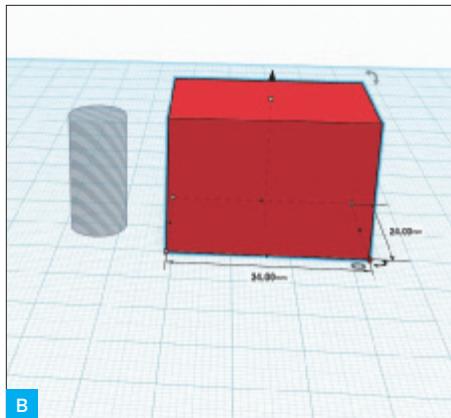
The height of the eraser is about 20mm, so stretch the cylinder to 20mm using the



TIPS

If you make a mistake, use the Undo button or type Ctrl-Z (Cmd-Z on a Mac) to undo the step.

It's often useful to view your design from a different angle. To do this, click on the arrow buttons in the upper left corner of the window. The + and - buttons are for zooming and unzooming.



top handle. Don't use the Shift key here, because you want to stretch only the height, not the diameter.

Now, with the cylinder selected, click the Hole icon (next to Color in the upper right corner of the workplane window). This will turn the cylinder into negative space, indicated by gray stripes (Figure A).

3. MAKE THE ROBOT HEAD

Make a box for the robot head. You can make it any size, as long as the width and depth will encompass the negative cylinder with at least 1mm–2mm on each side. I made a head that was 34mm wide × 24mm

deep × 24mm high, and placed it alongside the hole (Figure B).

4. ALIGN THE HEAD AND THE HOLE

To make sure the hole is in the center of the box, use the handy Align tool. Select both the box and the hole cylinder by shift-clicking each object, or click-dragging your cursor to create a Select box around them, or using Ctrl-A (Cmd-A on a Mac) on your keyboard to select everything. Look for the small gray circle with 3 white lines next to your selection. Click it and select Align.

Tinkercad will highlight both objects

with alignment dots. Click the 2 middle dots on the horizontal plane to position the hole in the center of the box (Figure C). Don't center the hole on the vertical axis, because that would seal the hole entirely inside the box, which would make it impossible to fit a pencil in the bottom.

5. COMBINE THE HEAD AND HOLE INTO A SINGLE OBJECT

Select both pieces and combine them into a single object by clicking the Group icon (Figure D).

6. MAKE THE HEAD HOLLOW

Make a hole box to put inside the robot's head. Size it 4mm smaller than the head in both width and depth. This will leave the head with 2mm-thick walls.

We don't want the inside to be completely hollow, as we need material at the bottom to hold the pencil in place. So leave about 10mm of material at the base by making your hole box 10mm shorter than the head. In my case, the interior hole is 30mm wide × 20mm deep × 14mm high (Figure E).

Use the Align tool to align the hole box to the top of the robot head, by selecting the topmost vertical dot (Figure F). Now select just the hole box and use the arrow handle to move it down 2mm (Figure G).

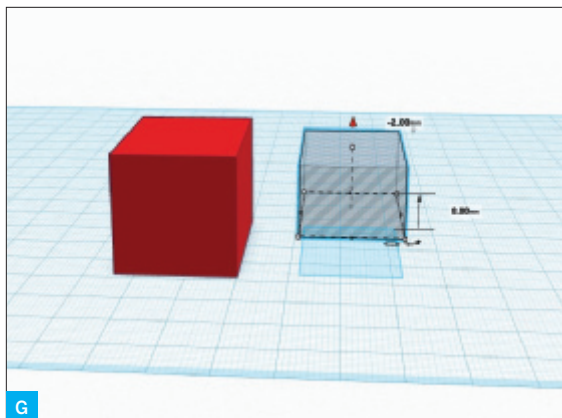
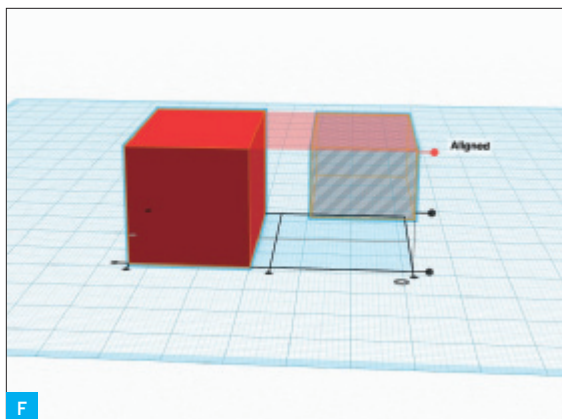
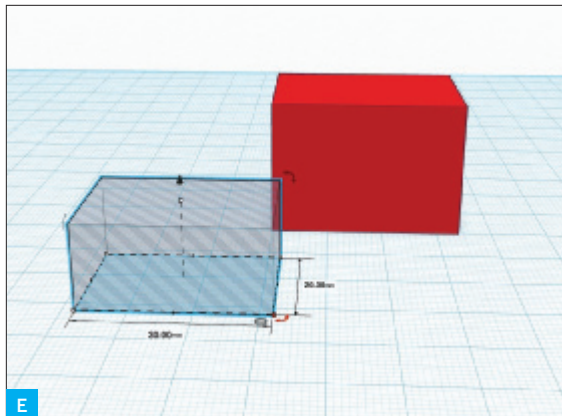
Select the hole box and the head box again, and align them on the horizontal plane (but again, don't click the vertical align buttons or else the hole box will move to the top or bottom of the head box).

Select all the pieces and combine them into a single object by clicking the Group icon. You now have a nice 2mm border on the top and sides of your hollow robot head.

7. MAKE YOUR ROBOT'S MOUTH

Start by making a mouthpiece with a box that's smaller than the robot's head.

To create the speaker-grill ridges, make a series of even smaller hole boxes. You can make one and create copies by clicking the Copy button, or using copy-paste keyboard commands, or clicking on the original and holding the Option key and dragging off a clone. Space them evenly apart and slide



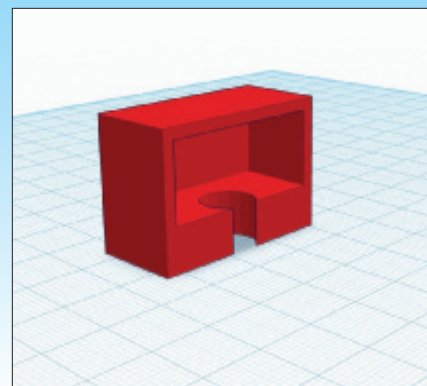
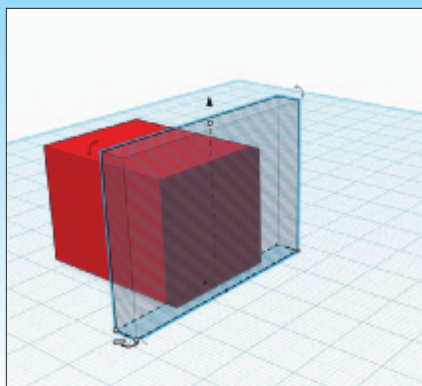
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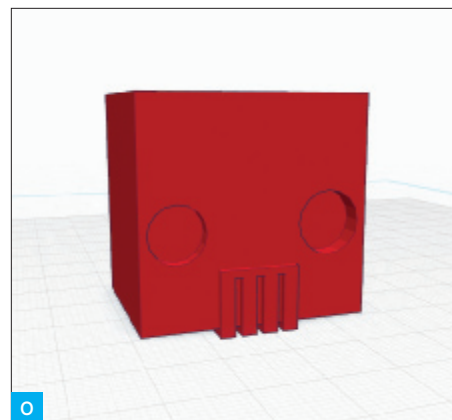
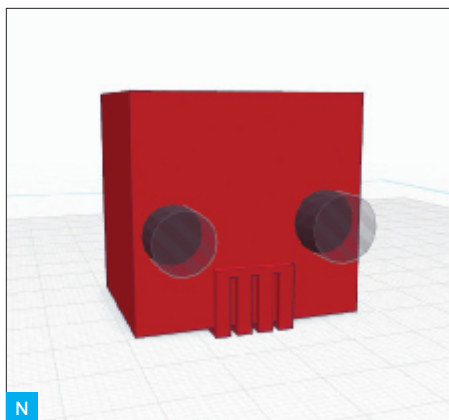
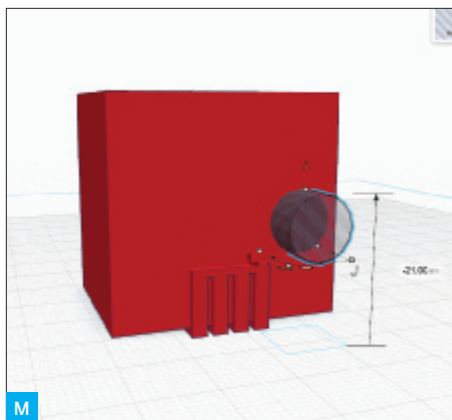
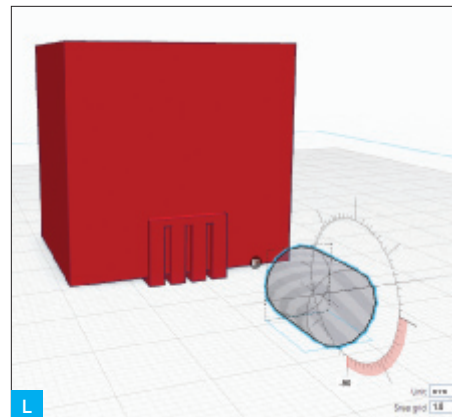
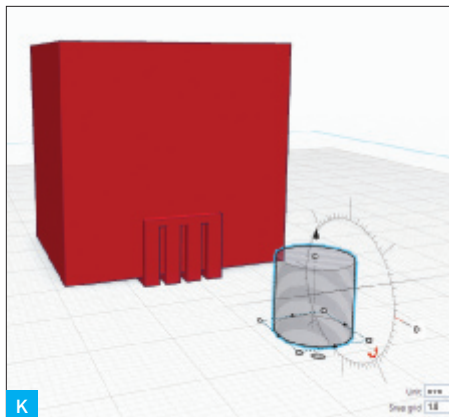
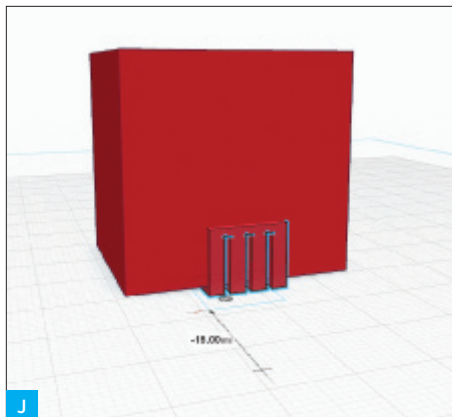
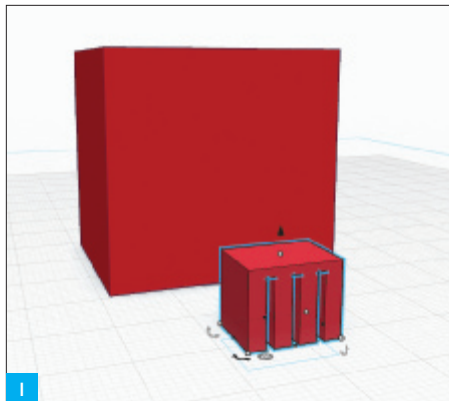
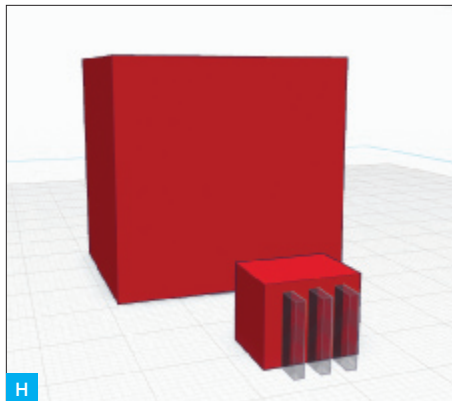
It's important to know the minimum wall thickness of the material you'll be printing in. For Shapeways' standard plastic, the minimum is 0.7mm, so 2mm is plenty of thickness.

X-RAY VISION

How can you verify that the hole box is positioned correctly inside the head? Here's a little hack that provides a clearer view inside your work.

Drag a box onto the workplane, turn it into a hole and change its dimensions until it's larger than one side of your design. Move the hole box so that it intersects your design, select all the objects, then click Group. Voilà! An interior view. Now, just Undo your way back to where you left off.





TIPS

By default, the workspace has a grid snap size of 1mm, so when adjusting the space between 2 objects, you can use the arrow keys to move the selected shape in 1mm increments.

Notice that a selected shape casts a shadow on the blue gridded plan of your workspace. Use this shadow to help you place your pieces into their proper locations.

them into the mouth box.

Then, with only the hole boxes and the mouth box selected, click Group. This will apply the hole objects to the box, cutting out the negative shapes, and turning them into holes (Figures H and I).

Place the mouthpiece so it sticks out from the front and bottom of the head box. (Don't push it in so deep that it intersects the pencil hole.) Group the head and the mouthpiece (Figure J).

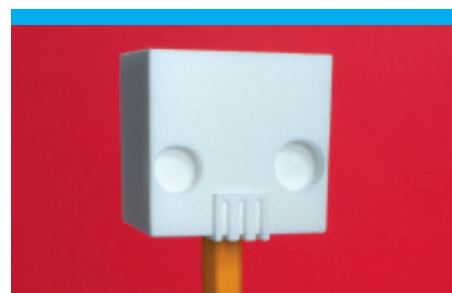
8. MAKE YOUR ROBOT'S EYES

To make the eyes, drag 2 cylinders into the workspace and make them holes. See those

curved arrows next to the cylinder? Click and drag on them to rotate the cylinder into the proper orientation (Figures K and L).

You need to raise the cylinders above the workplane grid so you can place them above the robot's mouth. Use the black arrow handle above the cylinder. Make the cylinders different sizes to add a little personality. Be sure the cylinders intersect with the head by 1mm. Select the cylinders and the head and Group them (Figures M-O).

Tada! You now have a print-ready robot-head pencil topper. Just hit the Print 3D button, select a printing service, and order yourself a new toy that you designed!



+ Check out the 3D model here: makezine.com/go/topperbot

Blake Maloof is a game designer at Toys for Bob (makers of *Skylanders*), and he sometimes writes about games for MAKE.

GETTING STARTED

» *Portable Greenery*
3D printed mini pots
from Wearable Planter.



3D PRINTING Without a PRINTER

How and why to use 3D printing services instead of a desktop machine.

► I'M INCREDIBLY LUCKY TO HAVE A JOB THAT EVEN TWO YEARS AGO, I NEVER WOULD HAVE IMAGINED COULD EXIST.

I create 3D-printed jewelry and own a business, Wearable Planter, all thanks to tools and technology that have only been available for a few years.

When I studied industrial design at Georgia Tech from 2006–2010, 3D printing wasn't a tool we used frequently. We learned how to use 3D design programs to mock up our projects, but we typically used the resulting 3D files for product rendering. Of course we had access to a 3D printer, but few people knew how to use it, and the models it made were fragile and expensive.

WRITTEN
BY
COLLEEN
JORDAN

It wasn't until my last semester of college that I worked on a project that required 3D printing. I handed the flash drive with my files to the lab assistant, thinking it would never work, and then watched with amazement as my jewelry piece was printed layer by layer exactly as I had intended.

Most people with the desire to imagine and prototype a new product don't have immediate access to a professional-quality 3D printer. The good news is that access to this technology is increasing at an unprecedented rate.

When I design a new product or piece of jewelry, I begin by creating sketches of what it will look like. This part of the process often takes the longest, as I am deciding

on the form and feel of the object. I then create a 3D model in SolidWorks, Rhino, or whichever program I feel will allow me the most creativity with my knowledge of the software. After I'm done creating, I export the file for printing, and I run checks with a program like Netfabb Studio to make sure it's suitable for printing.

I then use 3D printing services like Shapeways and Ponoko — both to prototype and to create my final products.

When I use these services, I have to wait two weeks or longer to see how my print turned out. That can seem like a long time, but it affords you a new perspective when you're forced to step away from your project momentarily. Sometimes when I get my first print back it's exactly what I was expecting, but often I see changes that need to be made, whether in material choice or wall thicknesses or other details.

The fantastic thing about using 3D printing services is that I'm able to run a business with tools that these companies have created — to experiment with different materials and new products inexpensively and with little overhead. In the past, creating a prototype could be costly, and production of even a limited run of items could be thousands of dollars. Also, I'm able to keep a limited inventory on hand because I can restock it quickly. This beats previous business models where I might have needed to order a cargo container full of pieces from overseas.

There are more advantages to using 3D printing services than just running a business. We're coming into a new era where mass customization is driving the production of new objects. Access to these technologies is now open to everyone, from beginners making character models with Minecraft, to doctors making personalized prosthetics.

For example, if you'd like to create your own phone case or dishware, but don't have any 3D modeling experience, you can use one of the many "creator" programs to make your own customized item. Sculpteo and the Society for Printable Geography recently released an app to create iPhone cases with the terrain of your favorite place. Shapeways lets you create a sake set by playing around with the shape of curves. These apps let you create your own unique manufactured item with minimal cost.

These companies have also begun to offer training so you can learn to use their tools. Ponoko offers online training classes, aimed at beginners, that are free to watch and participate in. Shapeways offers Skillshare classes to teach introductory skills as well as more complex, generative software.

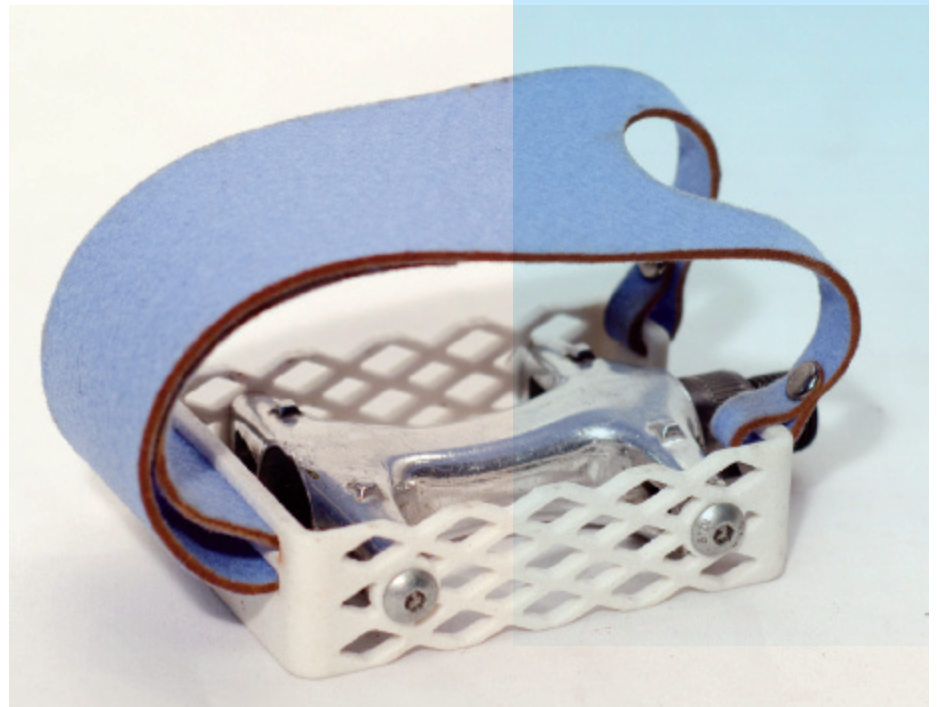
Sending your work off to 3D printing services has many advantages over using equally popular desktop 3D printers. You won't have the upfront investment of \$300 to \$2,000, and you won't spend time tinkering with settings and hardware. You also can create more complex and higher resolution objects, as desktop 3D printing still doesn't match the quality of professional machines.

The technology does come with its disadvantages. As this is a rapidly growing field, sometimes the demand is greater than the capabilities of these companies, and unexpected delays in lead times arise. The quality of materials isn't always as good as a similar mass-produced piece; 3D-printed plastic

parts, for example, can be more fragile than a similar injection-molded piece. And, importantly, not all of these materials are food-safe or suitable for use in toys. While these disadvantages may discourage you, keep in mind that this amazing technology wasn't available to the public even five years ago, and it's developing very quickly.

Colleen Jordan is a designer and maker who likes to create objects that make life more interesting. She is the founder of Wearable Planter (wearableplanter.com), and dreams of one day having a pet dinosaur.

If you have an idea you'd like to bring to life, there's no better time to see what may come from it.



Clockwise from top:
» A modified bike pedal using pieces of the original part, 3D-printed components, and a laser-cut strap. By Dan Emery, parts from Ponoko. » The Rocket Espresso Cup, 3D-printed in ceramic at Shapeways, by Craig Kaplan. » A Bit Cross by Michiel Cornelissen, 3D-printed in stainless steel at Shapeways.

SERVICE PROVIDERS

COMPILED
BY
COLLEEN
JORDAN
AND
STETT
HOLBROOK

► **IF YOU DON'T HAVE A 3D PRINTER, YOU CAN STILL ENJOY THE BENEFITS AND FUN OF TURNING A CAD FILE INTO A PHYSICAL OBJECT.**

So it's worth getting familiar with the growing number of 3D printing service providers. And commercial providers can print in a surprising range of materials not available to the home printer user. Even if you do own a printer, it's great to be able to turn a piece of art or technology you prototyped in plastic into something enduring, like titanium or stainless steel.



» A Strandbeest mechanism by Theo Jansen, printed in nylon on an EOS selective laser sintering (SLS) machine at Shapeways headquarters in New York. Dust it off and it's ready to walk.

SHAPEWAYS

shapeways.com

Shapeways caters to hobbyists and designers, offering high-quality prints in a wide range of materials, including sterling silver, stainless steel, and ceramic. They often have the lowest prices, but with production based in the Netherlands, their stated shipping times of 2-3 weeks haven't always been accurate. They're currently building a production facility in New York to meet demand.

Shapeways also offers a marketplace of designs where users can open their own shops. Because theirs is the most visible of these services, having a shop on their site is almost essential to getting started selling your work. There's little upfront cost or commitment.

PONOKO

ponoko.com

Ponoko offers 3D printing in a wide range of materials, from plastics and ceramics to stainless steel, gold plate, and Z Corp plasters. They also offer laser cutting and CNC routing in a huge variety of materials, so you can supplement your 3D-printed project with other custom parts.

Prints from Ponoko are generally very good quality and reasonably priced, but their pricing structure and system for uploading models are confusing. They do have a very good support staff who will go above and beyond to help you with any questions. Ponoko operates several regional production facilities, so printing and shipping times vary.

SCULPTEO

sculpteo.com

Material choices from this France-based company include multi-

colored plastic, resin, ceramic, and silver-plated plastic. The company sells a sample kit of materials for \$5. They offer a preview and live printability check that is very useful, and automatic model repair inside the web interface. They also offer many "creator" apps for you to begin making right away. Shipping times vary from 1-30 days depending on the material (upload your files for real-time estimates). Users may also post their objects for sale on the company's website.

I.MATERIALISE

i.materialise.com

Another 3D printing service based out of the Netherlands, they have a very clear and easy-to-use interface. Choose from more than 20 materials – titanium! – and print objects as large as 6 feet. Objects you create can be sold on the company's gallery. Depending on your location, objects ship in 1-5 days.

ZOOMRP.COM

zoomrp.com

Here's a self-service website for those who need plastic prototypes in a hurry. The site, a division of Solid Concepts, specializes in same-day 3D printing and shipping, with next-day and next-week options too. It's best suited for customers who know their way around CAD and 3D design. Fast, but it costs more.

REDEYE

redeyeondemand.com

RedEye, a division of 3D printing giant Stratasys, serves the architectural, medical, engineering, and aerospace industries with rapid prototyping. The company prints objects in various thermoplastics, UV photopolymers, and resins. Professional services, professional prices. Shipping time ranges from 1-2 weeks.

3D PRINTING RESOURCES



Adafruit's 3D Printing Skill Badge
adafruit.com/products/490
Declare to the world your proficiency in the world of 3D printing with this embroidered skill badge from Adafruit.

BOOKS

Practical 3D Printers – The Science and Art of 3D Printing
by Brian Evans, (Apress)

Expert tinkerer Brian Evans examines a number of different 3D printers and the software and electronics that make them work. You'll learn how to calibrate, modify, and print objects with your 3D printer.

Getting Started with MakerBot
by Bre Pettis, Anna Kaziunas France, and MakerBlock, (O'Reilly/MAKE)

Get a hands-on introduction to the world of personal fabrication with the popular MakerBot 3D printer. Not only will you learn how to operate, upgrade, and optimize your MakerBot, you'll also get guidelines on how to design and print your own prototypes. *Read an excerpt on page 92.*

Getting Started with RepRap
by Josef Průša, (O'Reilly/MAKE)

This book provides an overview of RepRap, the 3D printer that's the basis of nearly every inexpensive 3D printer on the market. You'll learn what it can do, how to model objects, and how to print the best parts possible.

3D Design for 3D Printing
by Matthew Griffin (due out September 2013; O'Reilly/MAKE)

One to keep an eye out for next year, this book arms those entering the passionate, fast-moving field of 3D design with practical 3D design techniques, and provides insights on designing for 3D printing through interviews and practical, hands-on examples.

3D MODEL REPOSITORIES

Thingiverse
thingiverse.com

The Grand Bazaar of the 3D printing world, Thingiverse is where the DIY community shares 3D models, laser-cut files, and PCB layouts of their projects and printers.

Although under the ownership of MakerBot, it remains an important resource for hosting and distributing files for many of MakerBot's competitors. Users select from an array of Creative Commons licenses, including the option for public domain.

Blender 3D Model Repository
blender-models.com

Blender 3D Model Repository is another free site that hosts shared 3D model files. It's designed to be a resource for Blender 3D modeling software users to download, submit, and share their collective knowledge. Along with models, the site features user-submitted Blender tutorials.

TurboSquid
turbosquid.com

TurboSquid is the leading paid 3D-model repository, with over 200,000 models to download.

NEWS

3Ders.org
3D printing news, updated daily.

Makezine.com/3Dprinting
The latest 3D printing news, reviews, and projects.

PHYSICAL DESTINATIONS

Hackerspaces
hackerspaces.org/wiki/List_of_Hacker_Spaces

Many hackerspaces have 3D printers you can try out. Visit your local hackerspace to learn what equipment they have.

TechShop
techshop.org

TechShop is a membership-based community workshop that has 3D printers available for members to use. There are TechShop locations in California, North Carolina, Michigan, Texas, and New York.

BRICK & MORTAR STORES

There are a few 3D printer stores sprinkled across the U.S. If you find yourself in one of these locales, don't pass up the opportunity to check these out!

Deezmaker
deezmaker.com
290 North Hill Ave. #5
Pasadena, Calif.

3D Creations
3dcreationsllc.com/store
161 W. Wisconsin Ave. #13
Milwaukee, Wisc.

MakerBot
makerbot.com/retail-store
298 Mulberry St.
New York, N.Y.

3D PRINTER HISTORY

RepRap Family Tree
makezine.com/go/repraptree
Shows the development of the RepRap 3D printer and its progeny.

PRINTERS, FILAMENT & PARTS

Maker Shed
makershed.com
Afinia H-Series, MakerBot Replicator 2, Printron LC & Jr., and Type A Series 1 – all reviewed in this issue are available now. Accessories too.

Printing Material Suppliers List
makezine.com/go/suppliers
A detailed directory of filament vendors that includes location, material specs, notes, and price.

UltiMachine
ultimachine.com
RAMPS electronics, PLA, and ABS filament.

Faberdashery
faberdashery.co.uk
PLA filament in a variety of colors.

Printbl
printbl.com
High impact, impact-modified and normal PLA.

ProtoParadigm
protoparadigm.com
Polyimide tape, polycarb, PLA, and ABS.

QU-BD
qu-bd.com
High-quality yet affordable extruders and heater pads.

➔ Sign up for the MAKE newsletter for exclusive 3D content and the latest deals from the Maker Shed. makezine.com



Ultimate 3D Printer

BUYER'S GUIDE

Here's how we torture-tested and rated 15 machines.

WRITTEN
BY
**MATT
GRIFFIN**

WHAT MAKES A GREAT DESKTOP 3D PRINTER? In September, MAKE invited me to put together a team of reviewers from the 3D printing community to advise MAKE's readers about the state of the art of DIY 3D printing.

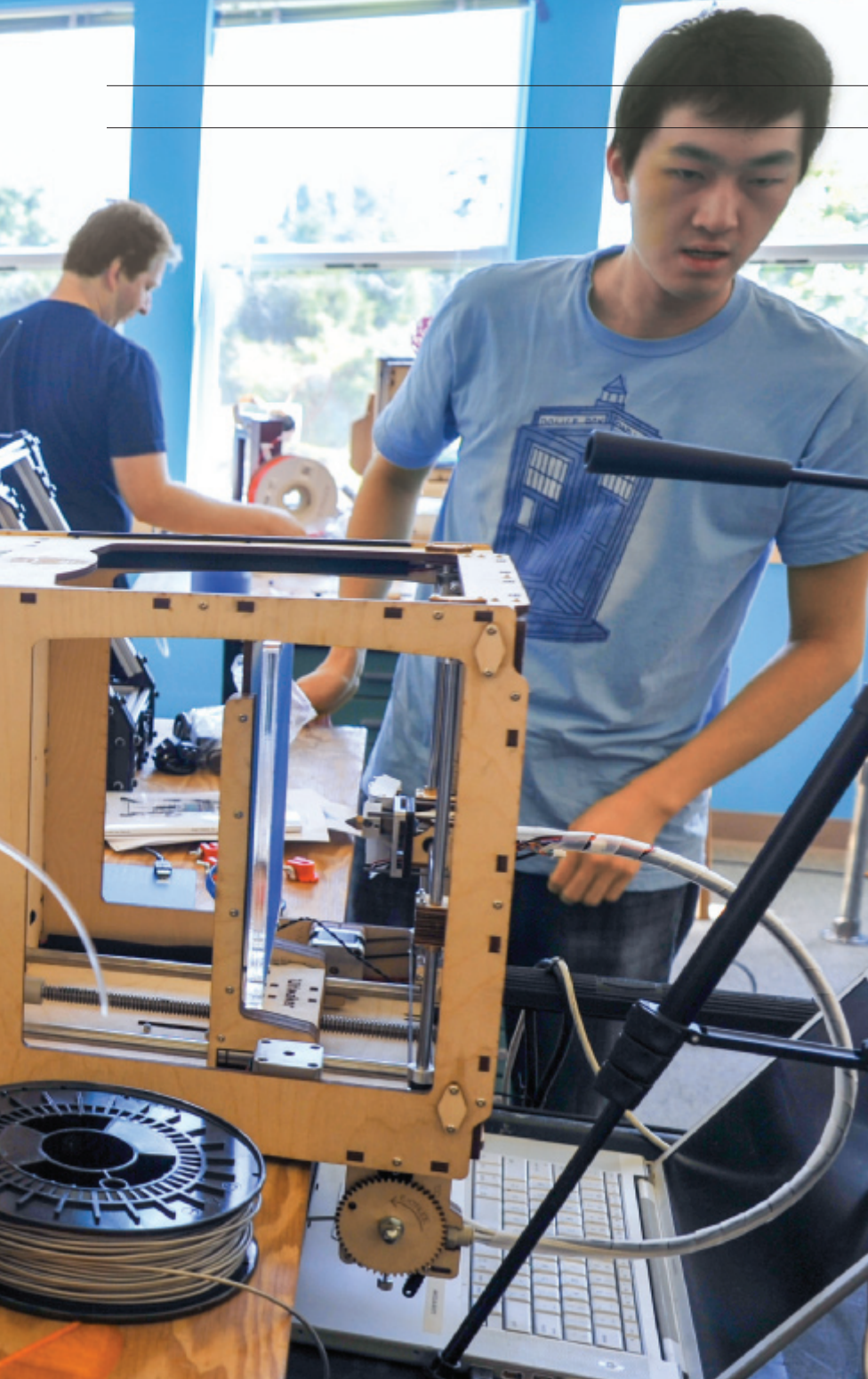
Our team investigated 15 of the most promising fused-filament fabrication (FFF) printers on the market — devices that melt and extrude plastic filament to form solid objects, layer by layer, the most popular method of 3D printing. We reached back to 2010 and into the future, previewing still-under-wraps machines weeks before their launch at World Maker Faire New York. But first we had the tough task of working out how to test and review these machines.

PERFORMANCE

What makes a successful print?

Here are key questions from our testing sheet. Our ratings indicate that reviewers disagreed strongly (1) or somewhat (2), were neutral (3), or agreed somewhat (4) or strongly (5).

- » Print job horizontal surfaces were “true”/no rippling/level.
- » Top layers of horizontal surfaces “capped” successfully, without gaps.
- » Vertical surfaces were “true.”
- » Vertical surfaces lacked gaps.
- » Vertical surfaces lacked tool/layer-completion seams.
- » Print remained fixed on plate.
- » Registration of layers was consistently accurate.
- » Plastic was consistent color.
- » Overall, this machine was precise.
- » Layer height remained consistent.
- » Discernable detail resolution approximated vertical resolution.
- » Layer-height resolution allowed for organic curves and folds with minimal stair-stepping.
- » Scale accuracy: size and shape of resulting parts matched intention.
- » Machine could handle overhangs up to 45° with minimal dropped loops.
- » Machine accurately reproduced sharp corners.
- » Output had no ripples or wobbles.
- » Surfaces were clean and smooth in places the artist intended.
- » Machine was fast.
- » Machine interface was reliable.
- » Rarely had to retry failed parts.
- » Could hit print and the machine would work without babysitting.
- » Print could be removed easily with tools or by hand.
- » Post processing (cleanup, support/raft removal) was quick and easy.



During the 3D Print Shop weekend, the MAKE offices became a vortex of 3D printers and the geeks who love them.

Every cresting wave in the alien invasion of the 3D printer into homes and maker-spaces — whether it's come from the factory floor, the academic laboratory, or the hobbyist's garage — has promised us the arrival of "the 3D printer industrial revolution." The signs are clear. From the explosion of the RepRap movement after 2007, to the launch of the popular MakerBot Cupcake CNC kit in 2009, to Printbot and other crowdfunding mega-hits of 2011, there is tremendous interest in devices that arm individual inventors, designers, hackers, educators, and hobbyists with an affordable toolset to make anything, in plastic.

But there are two questions makers must ask themselves: Is this the moment to choose a printer and join the plastic revolution? And if so, which machine do I choose?

We wanted to avoid staging a shootout to assess printers in terms of winning and losing, strictly on the specs. First of all, the frontier days aren't over. Many of the more capable machines we reviewed are harder to use, meant for the intrepid maker who's eager to get under the hood (though there are consumer-oriented options now too, for those who'd rather not tinker). Also, while

brilliant solutions have been brought to bear on mechanical design, the software tools are lagging, not only in toolpath generation (a challenging engineering problem) but also in usability (far less forgivable). Many of the machines that rely on open source hardware share these flawed software tools, and we're confident the user experience will improve as new talents continually contribute to improving them.

What core qualities does a maker look for in a 3D printer? We based a battery of test questions around four guiding principles:

- » A printer should be affordable for an individual to purchase and use regularly.
- » The hardware interface and software control tools should be easy to obtain, free or affordable, and documented for use.
- » The printer must produce pieces to suit the range of purposes that users create digital designs for: mechanical parts, product development, practical enclosures and mounting hardware, toys, scale models, and artistic/sculptural prints.
- » The machine should be worth a maker's time and money and should pull its weight on a workbench or desktop.

Tough demands, but ones that sharply distinguish DIY 3D printing from what's asked of industrial/commercial 3D printers.

In the early years, DIY 3D printers were balky and print jobs were limited to single, solid objects in one color of plastic. But a new wave is upon us. The quantity and diversity of DIY 3D printers that launched in 2012 are of a new order: they perform more reliably and tackle more sophisticated techniques. But do they work well right out of the gate, or do they require hours or even days of tuning and calibration?

The learning curve for operating some 3D printers can be steep. How deep should we dive into the forums and support resources in the pursuit of the capabilities of these machines? Should each of us bring our extensive background in operating other printers to bear on the machine at hand?

Grappling with these questions and believing strongly that vendors of DIY 3D printers need to better instruct users how to operate their machines, we settled on a compromise we described as the "Christmas Morning Challenge." What's it really like for a first-timer to open the box, set up this machine, and get it to fabricate that first printed object of acceptable quality?

TESTING METHODOLOGY

To approximate the beginner's experience, each tester was a "first-timer" on the printer they were assigned, and approached the test as if they had limited access to other resources or customer support lines.

Each 3D printer was unboxed and set up — or assembled from parts in the case of the kit printers. Then each machine printed the same four test objects (pictured at right) using the manufacturer's default settings. In addition, we probed the capabilities of machines that were bigger, smarter, faster, or finer than their peers.

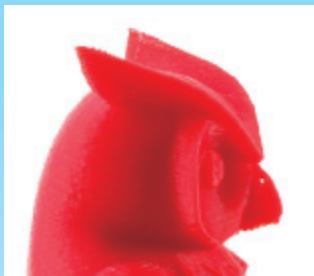
Each machine was then rated on a battery of questions, from ease of setup and calibration, to the quality of the hardware interface (if any) and software, to print quality, speed, and reliability. (Note that while manufacturers' claimed speeds vary wildly, in our default tests no machine was run faster than 80mm/sec.) See the full suite of questions at makezine.com/3dprinting.

We also invited printer vendors and their "superusers" to print the same objects and mail us their versions. We've shared these online at makezine.com/3dprinting, and we invite you to share your results too (see "Superusers: Participate!" below). As a result, we hope to provide balanced feedback that reflects the experiences of both first-time users and seasoned experts, and the true capabilities of each machine.

Read on to see what we found, but one thing became clear: while the field has further to go before the "revolution" offers desktop-grade printers suited to every home and workshop, there are a number of machines worthy of your serious attention. It's up to you to pinpoint which qualities are most important, how much time and money you want to spend, and what community of users suits you. If you're ready to start 3D printing, there's a printer ready for you here.

SUPERUSERS: PARTICIPATE!

Do you have one of the 3D printers in our test and want to share your prints of our test objects? Have a special trick or "pro tip" that might help others? Or perhaps you've tuned your slicing profile to perfection and can achieve models a newbie wouldn't believe? Please share your tips, files, and photos at makezine.com/3dprinting so that everyone in this high-energy, passionate community can benefit.



THE HOLE IN THE OWL'S BEAK

During MAKE's 3D Print Shop weekend, we noticed something startling about the owl print we'd done on the Afinia H-Series. The model had a tiny hole all the way through the top of its beak. We went through the other machines' test prints, and none were successful in printing the nostrils on the owl. Since then I've asked other owners of 3D printers if they knew the owl had nostrils, and none of them had. Their printers haven't managed the through-hole either. The hole in the owl's beak — the holy grail of affordable home 3D printing.

—Gareth Branwyn

THE CHALLENGE PRINTS



SNAKE by Zomboe thingiverse.com/thing:4743

This reinterpretation of a classic wooden toy features flexible ribs that are a great test for both horizontal accuracy on the plate (are the ribs evenly spaced and complete out to their tips?) and vertical registration (does each layer match perfectly with the one beneath?).



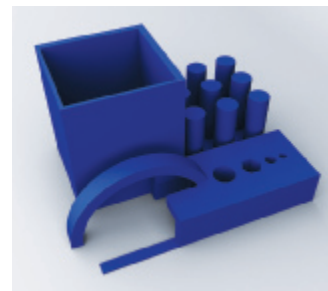
OWL STATUE by Tom Cushwa thingiverse.com/thing:18218

Designer Cushwa borrowed stone-cutting techniques to render feathers and character features for this popular owl figurine and modeled them to look great on a well-tuned printer. Printers that choke on these details may not be suitable for character and sculptural work.



NAUTILUS GEARS by Misha T. thingiverse.com/thing:27551

This model gives character to the classic snap-together gears that are a popular test object for 3D printers. It's quick to print, and you can tell instantly how well the machine reproduced the parts from how accurately the teeth mesh and the snaps snap, and whether the gears can rotate through more than one revolution without binding.



DIMENSION TORTURE TEST by Cliff L. Biffle makezine.com/3dprinting

To create a real "torture test" – a model guaranteed to challenge all FFF printers – engineer Cliff L. Biffle built a Frankenstein's monster containing all the geometry we needed to see in one small package. Thin and fat features, slopes and overhangs, bolt holes with precise dimensions, arcs, and separate towers all conspire to push a machine to its limits.

TEAM OF TESTERS



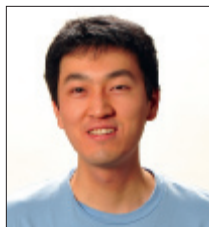
John Abella gets obsessive about hobbies. He currently owns three 3D printers.



Cliff L. Biffle is an engineer at Google and a member of Ace Monster Toys, a hackerspace in Oakland, Calif. He enjoys using science as a verb.



Gareth Branwyn is editorial director of MAKE. His master plan is to learn 3D printing so he can print replacement parts as his body falls apart with age.



Eric Chu is an engineering intern at MAKE. He enjoys yo-yos, robots, and fried rice.



Matthew Griffin is Adafruit Industries' community director. Formerly with MakerBot Industries, he's writing a book for O'Reilly on the 3D printing community.



Ethan Hartman is a customer service and documentation specialist for technology companies. He worked for MakerBot from 2009 until August 2012.



Lyra Levin builds things compulsively, preferably things she can climb on. She is currently in training to be a superhero.



Blake Maloof is a game designer at Toys for Bob (makers of *Skylanders*), and he sometimes writes about games for MAKE.



Brian Melani builds 120-pound robots in his free time. He is a MAKE engineering intern.



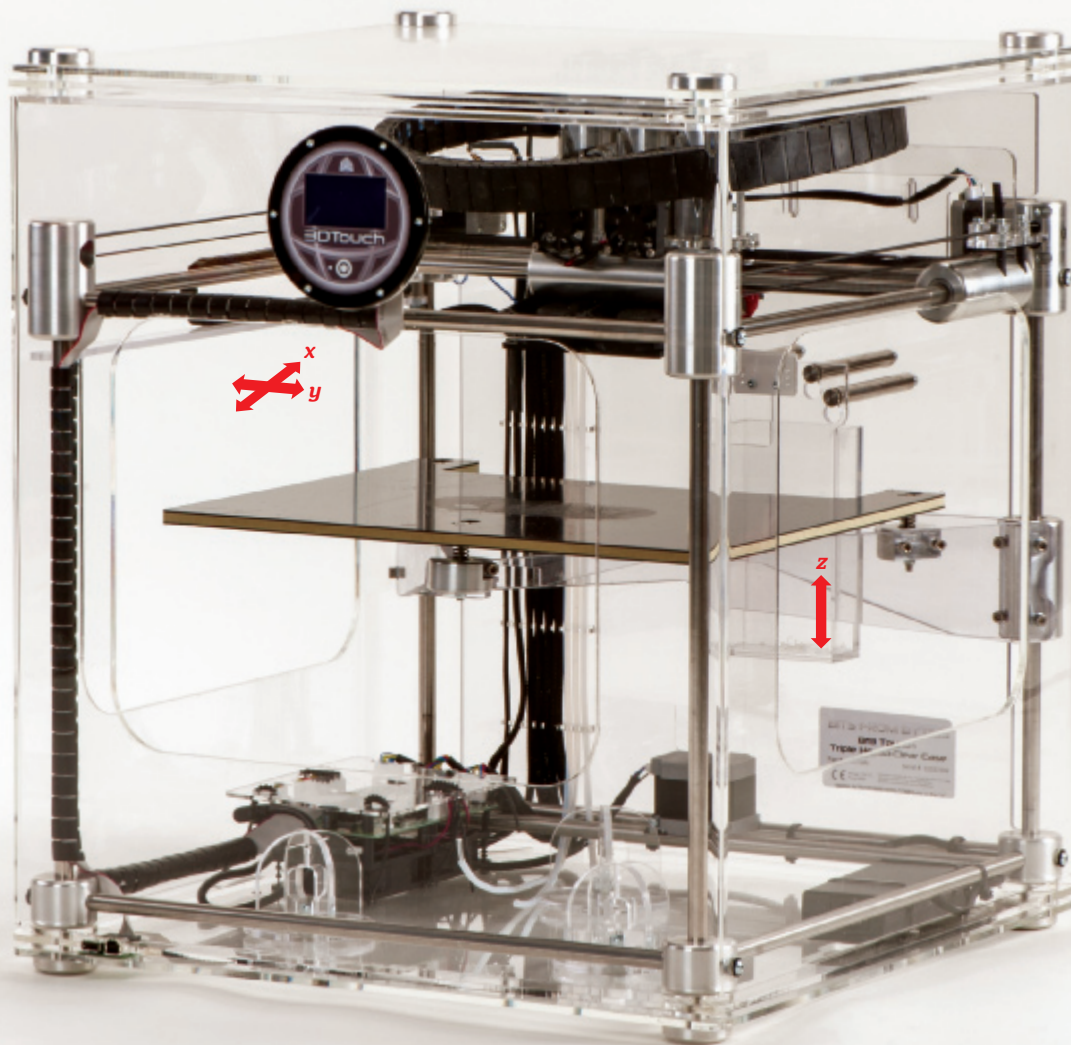
Emmanuel Mota is a creative director, filmmaker, photographer, and full-time geek. He got into 3D printing in 2012 when he built a RepRap from scratch.



Keith Ozar is a creative marketing professional from Brooklyn, NY. He empowers makers through special projects that highlight the potential of 3D printing.



Eric Weinhoffer is MAKE's product development engineer for the Maker Shed. He's been an owner-operator of 3D printers since interning at MakerBot in 2009.



» **Primo features** Triple extruders, touchscreen UI, automatic support material, best-built machine in our tests and one of the biggest

- » **Print volume** 7.3"×10.75"×7.9"
- » **Print speed** 15mm³/sec
- » **Print material** ABS, PLA, Soluble PLA
- » **Resolution (z-axis)** 0.125mm
- » **Machine software** Axon 2
- » **Slicing software** Skeinforge
- » **OS supported** Windows (XP/SP3, Vista, 7+)
- » **Open source?** No
- » **Price as tested** \$4,370 assembled
- » **Pedigree** RepRap Darwin
- » **Print without PC?** Yes, USB stick

3DTouch

Bits from Bytes / 3D Systems bitsfrombytes.com

Is this behemoth a beast or a dinosaur?

TESTED
BY
**ETHAN
HARTMAN
AND
ERIC
CHU**

WRITTEN
BY
**ETHAN
HARTMAN**

AMONG THIS GROUP OF FAIRLY DIMINUTIVE 3D PRINTERS, THERE WAS ONE HEAVYWEIGHT: Bits from Bytes' 3DTouch, one of the most impressive 3D printers aimed at the low-cost market. It's also one of the most expensive, priced at \$3,490–\$4,370. The 3DTouch is impressively built: with its massive, milled-steel connectors, it literally towered above the competition. It seemed as if it could engulf some of its competitors on its build platform — or perhaps print one out.

In several ways, the 3DTouch was an outsider in this group. Like several printers we tested, Bits from Bytes started from the RepRap movement but quickly moved toward the commercial mainstream, selling mainly to educators and professionals rather than focusing on the maker community. A brief search

turns up an official forum with some recent posts, as well as a defunct wiki or two: a poor showing in comparison to several other printers in this group. To top it off, Bits from Bytes was acquired by rapid prototyping giant 3D Systems in the fall of 2010.

2010 was also the year the 3DTouch was born, as the “BFB 3000.” It gained a new touch-based interface, as well as its current moniker, last year. That makes it one of the oldest designs in this roundup, even compared to the Mendel-based machines: its DNA (pardon the pun) goes back to the original RepRap Darwin.

You won’t mistake this for a Darwin, however. The 3DTouch’s build quality is exemplary; you’ll find sizeable, beautifully machined steel connectors holding everything firmly together. This is the only machine in the roundup that evokes the word “over-engineered.” The extruders, with a unique design that uses the screw of a bolt to push the plastic, are also made from milled steel. The 3DTouch had easily the best routing of internal cabling and filament. To top it off, everything is enclosed in an attractive case, available in clear or smoked acrylic.

There are a few other unique features. Though ABS is a primary material, the 3DTouch doesn’t use a heated chamber or platform; rather, its build surface is made of a plastic which extruded ABS or PLA melts into. It worked well, but prints were difficult to remove. We couldn’t figure out what the material was, but it mars easily when using the included print removal tool. Bits from Bytes says this is normal, and the platform is double-sided. We anticipate a typical user will need to purchase a replacement (\$87) at some point during the life of the machine.

Oh, and did I mention there’s a touchscreen? So you can control the 3DTouch with a touch-based interface? By touching it? Well, it’s quite good, with large icons and clear, concise prompts. A variant of this setup is in use for the 3DTouch’s sister printer, the Cube (see page 48). We felt that the platform leveling script could use a bit of work, but we had no other problems after a quick spin through the manual.

Setup was minimal — check the bed level, load filament, and print. Loading

filament was a bit of a chore, since it requires partial disassembly of the extruder, but our platform was good out of the box. We prepared our test prints using the Windows-only Axon 2 software, which worked well for the most part — impressively, it offers the ability to print automatically generated support material with a second extruder, something no other machine in this roundup can do out-of-the-box. (Otherwise, using multiple extruders in a single print is similar to the original MakerBot Replicator, which is to say rather clunky.)

Axon 2 wasn’t without its flaws: oddly, the functionality for preparing prints for the USB stick was labeled for SD cards. Also, we were surprised to find a Skeinforge window popping up after clicking through a few “Advanced” tabs; while it’s nice to have the tweakability offered by that familiar program, we had expected a proprietary slicer, like the one included with the Cube.

When we finally started printing, we expected top-notch results; after all, the 3DTouch is nearly twice as expensive as its nearest rivals, the LulzBot AO-100 and the MakerBot Replicator 2. That’s not quite what we got.

The 3DTouch’s output was only middle-of-the-road for this roundup. Fine textures were slightly messy, as if too much plastic was being pushed out. Larger-scale features seemed OK, but we did notice quite a bit of stringing between different areas of the prints, a problem no other printer in our tests had.

And, while it was very reliable, the machine was the slowest of the bunch, taking over an hour for the snake test.

CONCLUSIONS

It’s hard not to be a bit disappointed with the 3DTouch. With so much going right, it’s possible to overlook small things, but print quality is too big to ignore. The Axon 2 control software is in need of a tuneup, and we wonder if they could do better than Skeinforge for slicing; at the very least, some new profiles are in order.

Given the expense and the promise of this gigantic machine, it seems like a case of too little for too much. The massive, overbuilt 3DTouch doesn’t quite deliver on its massive price tag.

HOW IT COMPARES

Setup	5/5
Documentation	3/5
Ease of Use	3/5
Hardware User Interface	5/5
Machine Software	3/5
Slicing Software	3/5
Speed	1/5
Reliability	5/5
Print Quality	3/5
Accuracy	2/5
Support/Overhangs	4/5
Noise	3/5
Value	1/5

PRO TIPS

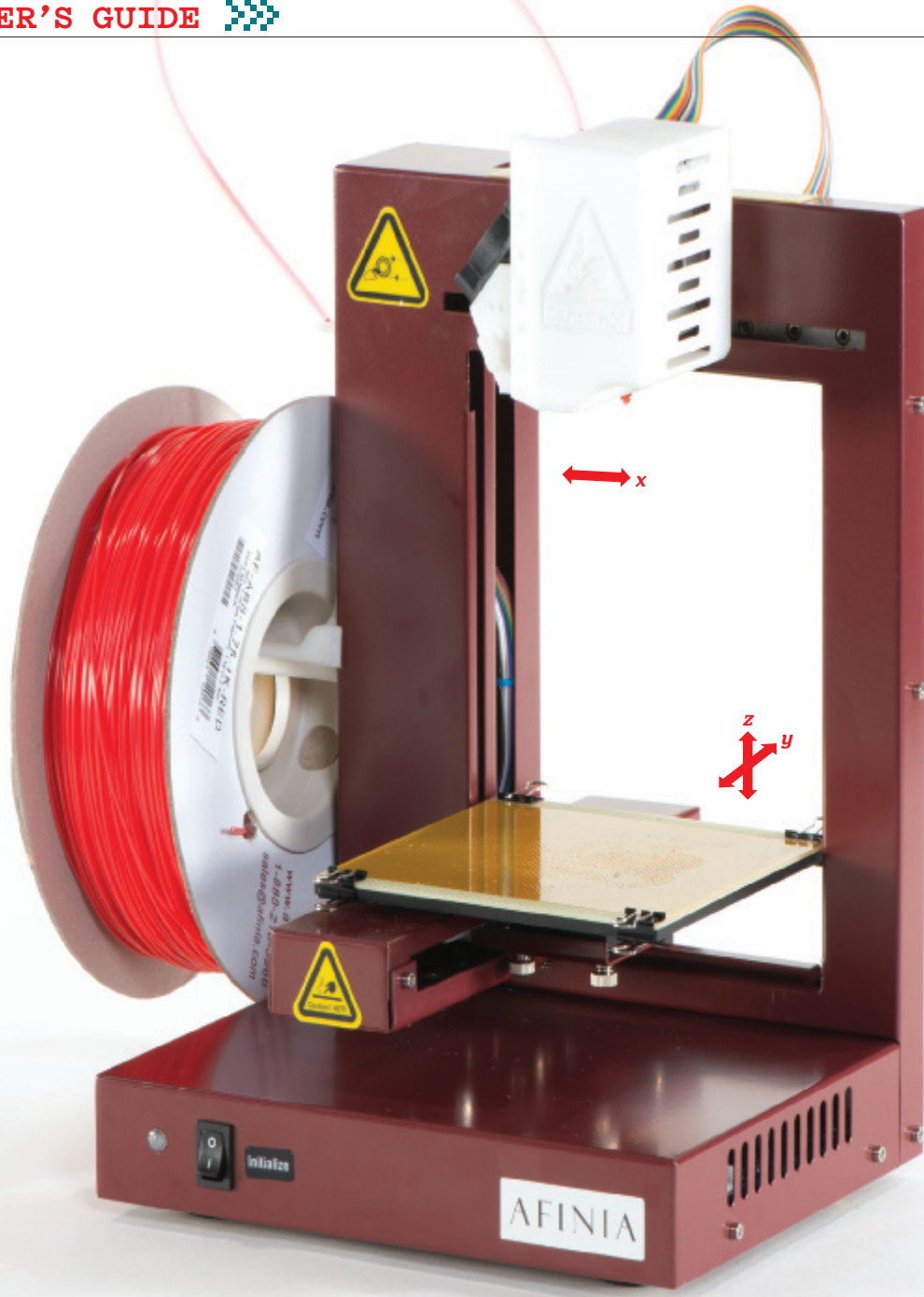
Load up the build platform; the Axon 2 software lets you print multiple objects in one go.

To tweak the extrusion rate, you’ll have to dive into Skeinforge. Try this spreadsheet to determine workable settings: thingiverse.com/thing:6427

THE DETAILS



Super solid construction, an excellent touchscreen, and check out those crazy extruders.



» **Primo features** Heated platform, great print quality and software, U.S. tech support

- » **Print volume** 5.5"×5.5"×5.3"
- » **Print speed** 3-30mm³/sec
- » **Print material** ABS, PLA
- » **Resolution (z-axis)** 0.2mm
- » **Machine software** Afinia 3D
- » **Slicing software** Afinia 3D
- » **OS supported** Windows, Mac
- » **Open source?** No
- » **Price as tested** \$1,499 assembled
- » **Pedigree** PP3DP Up
- » **Print without PC?** Sort of ...

Afinia H-Series

Microboards Technology afinia.com

Easy to use, with feature-rich software and impressive print quality.

WRITTEN BY KEITH OZAR
 TESTED BY KEITH OZAR AND ERIC WEINHOFFER

THE COMPACT AFINIA H479 IS A VERSION OF PP3DP'S UP PLUS 3D printer, rebranded for the U.S. market. It's got a single extruder and runs via USB off Mac or Windows machines, with no onboard controls except an Initialize button and a flashing status indicator. But despite the no-frills hardware, it's a surprising little performer that's ideal for beginners.

SETUP

The printer's tidy size and appearance are appealing: it sits about 10"×10"×14" high on the desktop, weighs just 11lbs, and is sturdy for transport. It ships fully assembled and takes only a few minutes to set up. Loading the filament, leveling the platform, and calibrating the machine were easier than expected, thanks to documentation that's straightforward and easy to follow, with an in-depth manual and a one-page Quick Start Guide for those wanting to jump right in.

The status light tells you in a series of red and green flashes if the printer has been initialized, if it's ready to print, if the extruder is heating or extruding, and if it has started or stopped printing — but if you don't have the manual in front of you, this can be confusing. It's a constant reminder that the lack of an onboard control panel is a weak spot for this printer. The machine also makes a loud beeping sound as it begins initializing and printing, which reminded us of a truck backing up, though it prints quietly.

Using the proprietary software package Afinia 3D, you can add multiple objects to the same platform, choose to build with a raft, set variables for the support structure, and choose resolution and a variety of infill options. Just select the overhang angle beyond which you'd like to have support material, and the software automatically creates the support for any angle that exceeds it.

Once your design is to your liking, it's as easy as pressing Print. There's no need to deal with G-code or slicing software — it takes care of those elements for you. Although the software is "closed" and can be prone to crashing, its features are robust and relatively intuitive.

PERFORMANCE

Print quality was quite good — we were surprised by how great the first print looked (the snake), and subsequent prints like the owl statue confirmed it: sharp corners, clean overhangs, and true vertical and horizontal surfaces. Dimensional accuracy was off by about 1% on our torture-test object, with holes just slightly undersized, though this might be attributable to shrinkage of the ABS plastic.

The Afinia was reliable, too; we didn't have to babysit it or retry failed parts. The documentation mentions the capability of pausing mid-print to swap out filament and resume where the extruder left off, but we didn't get a chance to test it. This technique would be a great option if you wanted to print a multicolored object with a single extruder.

While this model is about the same size as the original Up released two years ago, its build volume is still decent-sized compared to today's DIY printers, about a 5½"-cubed range of motion. Both ABS and PLA filament can be used, and the printer comes with a 1.5lb ABS spool. (Afinia offers additional spools in natural, black, red, blue, yellow, and green, or you can buy from other manufacturers.) It also comes with work gloves and hand tools that include a woodcut knife, screws, scraper, pliers, brush, nozzle wrench, hex wrench, and tweezers.

Also provided are a set of FR-4 perf boards for the print surface that offered surprisingly successful printing adhesion, and could be cleaned easily using the included tools to push plastic up through the holes. The style of rafting and support offered by the software also help with both adhesion and removal.

Unfortunately, there is no SD card or USB flash drive on the Afinia. You can print from your computer via USB and then disconnect once the job has started printing, since the file now resides in the printer — but we'd prefer to be able to print totally untethered.

Also, the print speed was comparatively slow next to many of the more recently designed 3D printers we tested.

CONCLUSIONS

The Afinia H-Series 3D printer stood out as one of our favorite 3D printers in the challenge. Straight out of the box, using the default 0.2mm resolution settings (about 0.008" or 8 mils), we printed some of the best-looking examples of the challenge prints.

While there are limitations to how far you can tune, tweak, or tinker with a closed-box machine, the Afinia offered the best printing quality with the least amount of effort, overshadowing any of its limitations.

HOW IT COMPARES

Setup	5/5
Documentation	5/5
Ease of Use	4/5
Hardware User Interface	3/5
Machine Software	4/5
Slicing Software	5/5
Speed	2/5
Reliability	5/5
Print Quality	5/5
Accuracy	5/5
Support/Overhangs	5/5
Noise	4/5
Value	4/5

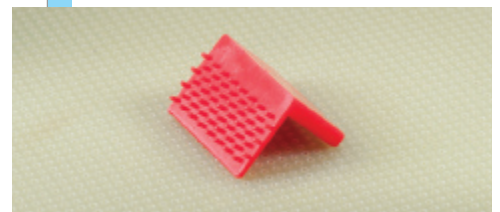
PRO TIPS

Preheat the platform 15 minutes to prevent ABS prints from warping.

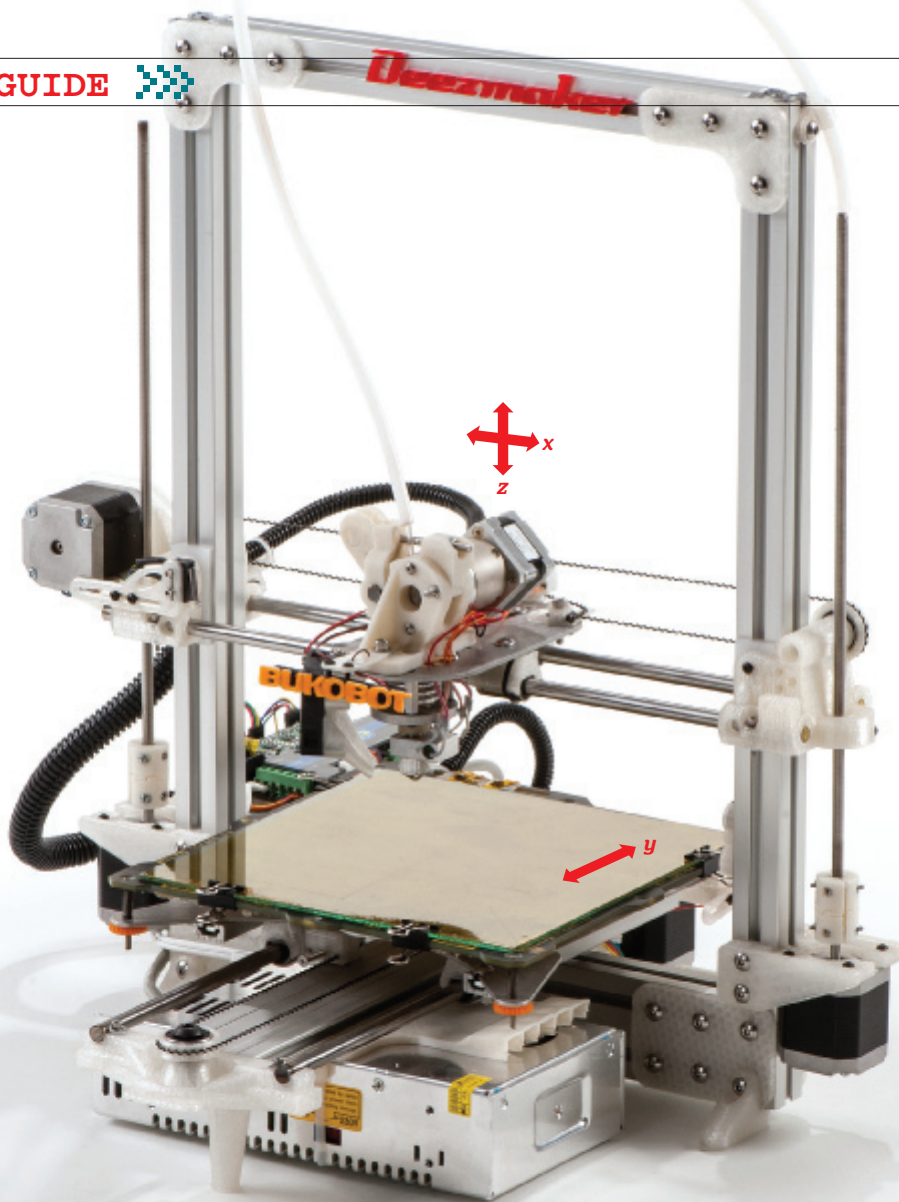
If the ABS looks white where you remove the raft or support, warm it with a heat gun to regain color.

Don't be limited by platform size. To build large objects, slice models creatively and glue them, create snap-together joints, or articulate them with moving joints or gears.

THE DETAILS



The unique perf-board build platform performs well, and the software slices, generates support, duplicates, and places models for printing — all automatically.



» **Primo features**

Extendable in any axis, synchomesh cables, Azteeg electronics, custom Tatsu drive gear, printed fan shroud, optional dual extruders

» **Print volume** 8"×8"×8"

» **Print speed** 120mm/sec

» **Print material** PLA, ABS, PVA

» **Resolution (z-axis)** 0.1mm-0.3mm

» **Machine software** Repetier-Host

» **Slicing software** Slic3r

» **OS supported** Windows, Mac, Linux

» **Open source?** Yes

» **Price as tested** \$1,385 assembled

» **Pedigree** RepRap Prusa Mendel, Printrbot, Wallace

» **Print without PC?** Optional, SD card

Bukobot 8

Deezmaker deezmaker.com

Nimble, expandable, and smartly innovative, the Bukobots will make a lot of new RepRap fans.

TESTED
BY
**MATT
GRIFFIN
AND
JOHN
ABELLA**

WRITTEN
BY
**MATT
GRIFFIN**

DIEGO POQUERAS EXPLORED HIS PASSION FOR 3D PRINTING at monthly meetups at the Crash Space hackerspace in L.A., where he got to know a range of printers and their operators, including future Deezmaker collaborator Rich "Whosawhatsis." It was a great way to learn about the strengths and weaknesses of each machine. The fruits of his investigations? The promising new RepRap Buko framework and an entire line of Deezmaker Bukobot printers, inspired by Prusa Mendel, Printrbot, and Wallace models and augmented by his own engineering ideas.

Poqueras launched his printer on Kickstarter around the time of Maker Faire Bay Area 2012, and his project was 400% funded. Recently he was joined by Whosawhatsis, developer of the RepRap Wallace framework, and the two

opened a Pasadena-based storefront where they sell printers from Deezmaker and other vendors, and offer a hacker-space where people can experience 3D printing firsthand.

The Bukobots have a unity of appearance that I found immediately pleasing. The printed brackets and couplers that hold the machine together are fabricated in clear PLA, granting an otherworldly look: a machine made of aluminum and ice. The two-color Deezmaker and Bukobot logos mounted to the frame offer an enticing preview of what's possible by swapping filament mid-print.

With Bukobot, Deezmaker introduces the RepRap Buko framework, planned from the ground up to take full advantage of its structural components — Misumi extruded aluminum beams, PLA printed brackets and joins, and synchromesh timing system — in an effort to limit the number of parts and total cost, and avoid the temptation of overbuilding (with its hidden risks of over-constraint). The machine features the simplified X-Z gantry and front-to-back Y build platform used by Printbot and the Wallace, providing rigidity and strength. And uniquely among RepRaps, the Buko design is expandable in any axis by substituting longer Misumi beams.

The use of synchromesh timing cables is one of Poqueras' most distinctive innovations. They're constructed from a core wire wrapped by a tightly spiraling second strand that helps to resist stretching even when twisted along elliptical paths. Synchromesh pulleys lock into the spiral cable, reducing the backlash that occurs when timing belt assemblies lose tension.

Typically indicated for space-constrained projects like robotics and desktop 2D scanners, synchromesh is an efficient, inexpensive solution allowing small movements at high speeds without introducing slop. Bonus benefit: the customer can cut her own cables when expanding the build area, without purchasing new custom belts for every configuration.

SETUP

We tested the Bukobot 8 Vanilla version, with a single extruder; the Duo version offers two extruders. Setup took only about a half-hour, and the documentation

included with the printer provided most of the information necessary to tune the machine, though we did have to seek help to figure out the baud rate.

A great touch: printed cable tensioner disks make it easy to perform small dialing-in adjustments.

There's no SD card slot on the Azteeg X1 electronics, so get the X3 upgrade if you want to print untethered. Our unit lacked even a power switch, which seems perhaps a little too streamlined? A noisy power supply gave us pause but caused no issues during our testing.

PERFORMANCE

While we felt confident the gantry was square to the plate, we had adhesion troubles with both ABS and PLA until we covered the platform with blue painter's tape — a common solution out in the field for printers that extrude PLA. This improved adhesion significantly, and we were able to print a fine-looking snake using Printbl's new Diamond Age PLA, which Deezmaker included with the unit.

After shifting to the printed fan shroud attachment, which allows for active cooling of the top printed layer, we had our best successes printing PLA. The torture-test results were promising: adhesion issues knocked off the base of the unsupported arch, but the vertical and horizontal surfaces were all true.

Printing results generally were better than average, and the owl statue in particular, while not the best in our test, promises that this unit, when really dialed in by an operator, will compete aggressively for quality at its price point. Also promising, Deezmaker is working closely with filament supplier Printbl to tune the extruders to suit rubberized PLA and other experimental materials.

CONCLUSIONS

Deezmaker's nimble Bukobot 8 stands on the shoulders of giants to leverage the best features of the Prusa Mendel, Printbot, and Wallace projects, and it offers innovations likely to keep the RepRap Buko framework in the public eye for some time. It's an attractive, design-forward printer with a lot of well-thought-out features that should attract a broader audience to the RepRap movement.

HOW IT COMPARES

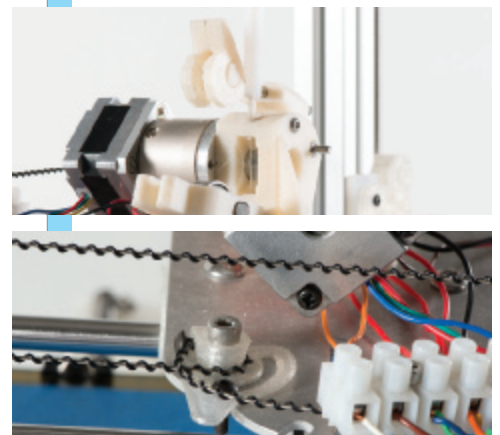
Setup	4/5
Documentation	4/5
Ease of Use	3/5
Hardware User Interface	3/5
Machine Software	3/5
Slicing Software	3/5
Speed	5/5
Reliability	5/5
Print Quality	4/5
Accuracy	4/5
Support/Overhangs	4/5
Noise	3/5
Value	4/5

PRO TIPS

Forget the Kapton tape — cover the print bed with blue painter's tape for better adhesion of PLA.

When printing PLA, take advantage of the clever printable fan shroud attachment to provide active cooling from the extruder's cooling fan directly to the surface of the printed part.

THE DETAILS



The Bukoschnozzle hot-end has an idler latch for easy filament swapping mid-print. (The custom extruder gear is from Marples Gears, a NASA Mars rover contractor.)

Synchromesh cables replace belt pulleys and help counter backlash.



- » **Primo features** Wireless printing, touchscreen interface, great manual, easy filament install, "magic glue"
- » **Print volume** 5½"×5½"×5½"
- » **Print speed** 15mm³/sec
- » **Print material** ABS (proprietary cartridge)
- » **Resolution (z-axis)** 0.01"/0.25mm (10 mil)
- » **Machine software** Cubify Client Software
- » **Slicing software** Cubify Client Software
- » **OS supported** Windows (XP/SP3, Vista, 7)
- » **Open source?** No
- » **Price as tested** \$1,299 assembled
- » **Pedigree** Similar to PP3DP Up
- » **Print without PC?** Yes, wi-fi, USB stick

Cube

3D Systems cubify.com/cube

With wi-fi printing and OK print quality, the reliable, easy-to-use Cube makes a move for the mainstream.

TESTED
BY
**JOHN
ABELLA
AND
MATT
GRIFFIN**

WRITTEN
BY
**JOHN
ABELLA**

WHEN YOU THINK ABOUT HOBBYIST 3D PRINTING, the name "3D Systems" doesn't immediately come to mind. The company is trying to change that with the Cube, its recent entry into the low-end fused-filament fabrication market.

The first thing you notice about the Cube is its style. No plywood, loose wires, or zip ties: this machine is made to be a consumer appliance more than a hacker plaything. This level of design quality carries into the included documentation, which was some of the most thorough of the machines we tested.

The Cube brings a mix of unique features as well, including the ability to

print via wi-fi or USB, a well laid-out touchscreen control panel, and a completely new item that no other manufacturer had: “Magic Cube Glue.”

SETUP

Wi-fi and USB printing both worked as advertised and performed well. The Cube can use your WPS wi-fi network, but we had better luck printing directly via its ad-hoc network. You’ll have to disconnect from any other wi-fi temporarily; thankfully it doesn’t take long.

Like most printers that use ABS plastic filament, the Cube uses a heated build platform to help with adhesion and to prevent warping on larger prints. The open-air nature of the printer seems like it would be prone to warping, but the included “magic glue” worked great to keep prints stuck to the build surface. This mystery substance washes away with water to cleanly release prints from the removable platform.

The device is driven by a touchscreen interface that allows the user to configure nozzle height, wi-fi settings, and other details, as well as showing the status of current print progress and other system indicators.

PERFORMANCE

None of these industrial design accomplishments matter if the printer doesn’t perform, and the Cube performed well. Testers were able to print all weekend without any failed prints, a record that almost no other device could match.

The default performance of the Cube out of the box had a few flaws worth mentioning, the first of which was speed. In our standardized print tests, the Cube was one of the slowest in the field. There was also a loud, resonant buzz related to certain movements, but from discussions with other owners, it sounds like the problem was specific to our test unit.

By default the printer and software are configured to print using rafts and support structures, both of which add to printing time and post-processing time, but which helped in the most demanding print tests. Both options can be turned off, but doing so will generally degrade the print quality.

In the print accuracy tests, the Cube

had problems similar to many of the printers we evaluated: holes were too small, and other dimensions were not accurate. Several testers felt that the Cube appeared to be extruding too much plastic on all prints, something that could be related to the color of the ABS being printed, humidity, or other factors.

The Cube isn’t an open source product, and the Cubify software that drives it runs only on Windows 7 or higher. While many of the software packages used in our tests allow for endless tweaking, the Cubify package is relatively stark. There are basic switches for enabling/disabling support and rafts, but not much control over layer height, infill percentage, extra shells, or customizing support structures.

The Cubify software works with the same STL files as the other printers we evaluated, and also supports proprietary .creation files. 3D Systems has a website where designers are uploading various creations that can be downloaded (for a fee) and printed on your printer. It’s an interesting option for people who aren’t looking to design their own files, but we suspect it’ll be a hard sell while free options like Thingiverse exist. Each new printer comes with 25 free .creation files to get you started.

The Cube works with special filament cartridges available only from 3D Systems. They weigh in at about 1lb of usable ABS for \$50, making them more costly than generic spools.

Finally, the Cube is a sealed device that’s not intended to be hacked. None of the electronics, steppers, or motion control mechanisms are visible or accessible without removing the case, meaning that any necessary repairs will likely involve a trip to the post office.

CONCLUSIONS

The Cube is a well-designed and well-documented unit that prints reliably and brings helpful new standard features to market. It looks great on your desk, but doesn’t offer the ultimate build quality. Rather than being a printer for the bold tinkerer who keeps abreast of the newest firmware and software, this is a machine for someone who wants to simply hit “Print” — and have a machine that looks nice printing.

HOW IT COMPARES

Setup	5/5
Documentation	4/5
Ease of Use	5/5
Hardware User Interface.....	5/5
Machine Software.....	3/5
Slicing Software	3/5
Speed.....	1/5
Reliability.....	5/5
Print Quality	4/5
Accuracy	2/5
Support/Overhangs	4/5
Noise	2/5
Value	4/5

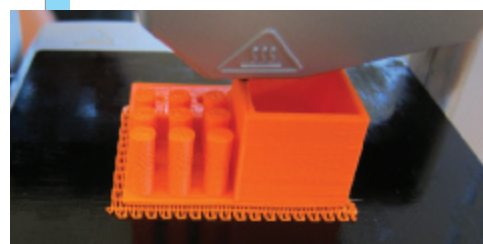
PRO TIPS

Once a print has been queued over wi-fi, you can shut down the PC.

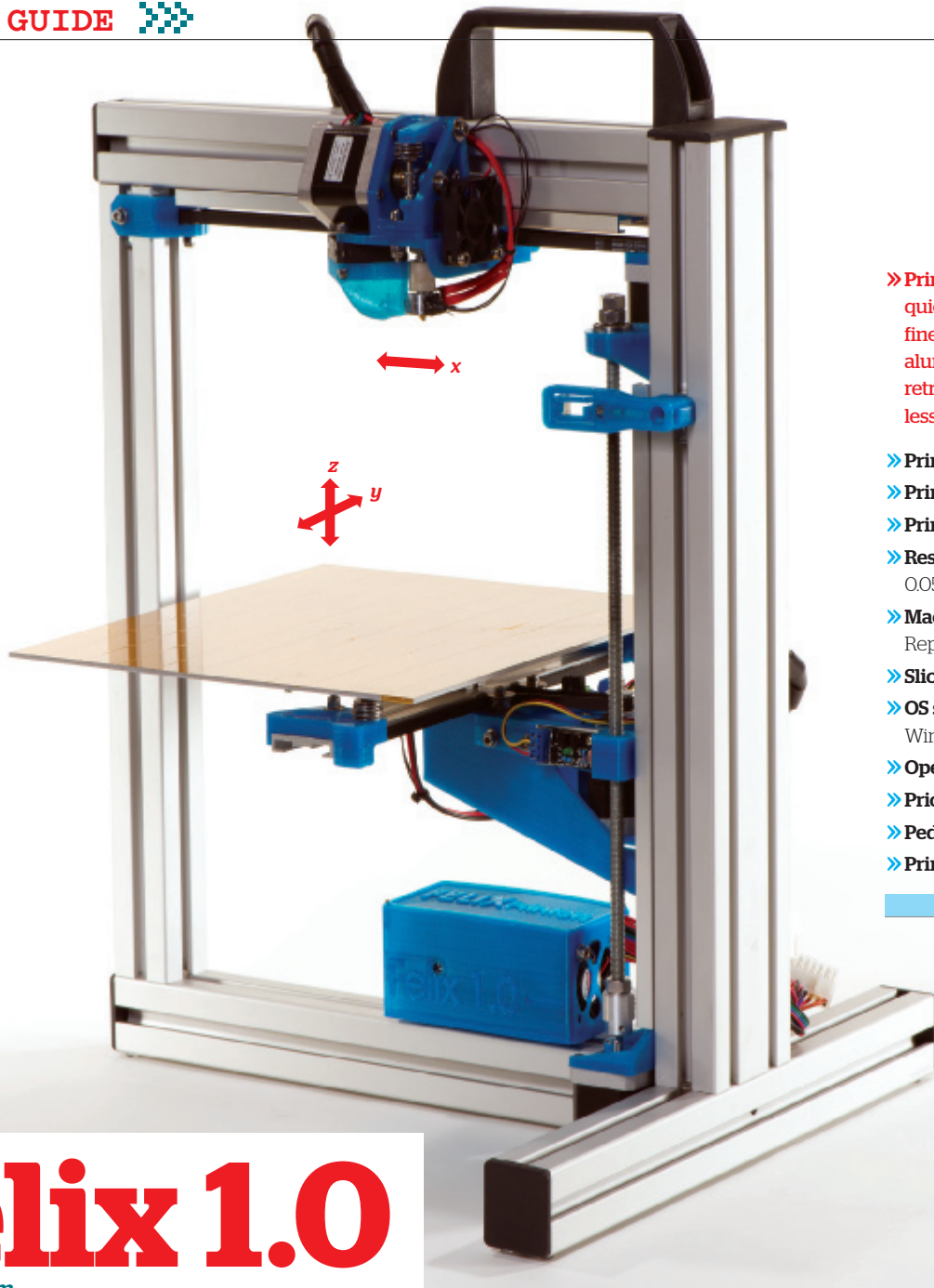
Soak the build platform and the print in water to dissolve the “magic glue.”

Check out Cubify Apps (cubify.com/apps.aspx) for new ways to use the Cube.

THE DETAILS



The only home/hobby printer with wi-fi printing and dissolvable glue to secure your print, the Cube's also got the easiest hardware interface — a touchscreen.



» **Primo features** Extremely quiet, large build volume, fine Z resolution, rigid aluminum frame, good retraction for near-stringless builds

» **Print volume** 10.2"×7.8"×7.8"

» **Print speed** 150mm/sec

» **Print material** PLA

» **Resolution (z-axis)**
0.05mm–0.35mm

» **Machine software**
Repetier

» **Slicing software** Repetier

» **OS supported**
Windows only

» **Open source?** No

» **Price as tested** \$1,165 kit

» **Pedigree** Original

» **Print without PC?** No

Felix 1.0

felixprinters.com

Quiet and capable, the Felix is a true DIY printer — bring your toolbox and your patience.

TESTED
BY
ERIC
CHU
AND
BRIAN
MELANI

WRITTEN
BY
ERIC
CHU

GUILLAUME FELIKSDAL WAS THRILLED WHEN HE BOUGHT HIS FIRST 3D PRINTER KIT. Finally he could prototype parts for his humanoid walking robot! But he became frustrated by the days-long process of building and calibrating it. Like a punk rocker inspired to play by seeing the Sex Pistols or the Ramones, Feliksdal told himself, "I could do that. I could do better!"

Today the Dutchman sells his own kit, with RAMPS 1.4 electronics, a rigid frame made of aluminum extrusion, and a large build volume that competes with any DIY printer out there.

KIT BUILD

The PDF assembly instructions are well done, with photos and diagrams for each step, though some steps required rereading several times.

The kit requires hand and power tools such as a file and a drill, so it lacks the “screwdriver-only” appeal of some other kits. One tedious step was to file flats onto the stepper motors.

It took us longer than the estimated 5-10 hours to finish this build, and we’ve built kit printers before.

SETUP

Software setup was documented at each step with screenshots, making it very easy. Several steps required entering directories of files and folders, which probably could have been automated. Fortunately, you only do them once.

The Felix version of Repetier bundles Skeinforge and Slic3r under the Repetier front end, so you can choose one or the other when slicing your STL file. We had trouble getting Skeinforge to start slicing but that was fixed by running Repetier as an Administrator in Windows. Felix came with a handful of slicing profiles, which are nice to have, but their settings aren’t documented so you’ll have to dig or experiment to see what each one does.

The manual guides you all the way to your first print and includes troubleshooting steps for when things go awry.

Leveling the bed and setting the Z height were a bit of a challenge. You use a wrench to loosen a nut under each of the three leveling screws until the aluminum bed is leveled. The Z limit switch is an optical end-stop that’s triggered when an opaque object blocks its IR beam. By turning a screw on the printed Z end-stop (which blocks the IR beam), you move it up and down, thus adjusting the Z home position. The LED supposedly turns off when the end-stop is triggered, but ours only got very dim, making it hard to know exactly where the Z home position is triggered.

The X and Y belts are extremely easy to tension: just turn one screw on each axis to tighten them.

The Felix’s extruder uses a spring-loaded tensioning mechanism that presses a ball bearing against the filament and

extruder gear. The proper tension was tricky to figure out; ours worked well when we set it so that the ball bearing rests against the extruder gear before putting in the filament.

PERFORMANCE

We had some roadblocks getting our machine printing the way it’s supposed to. First, two of the Pololu stepper drivers were bad, one unresponsive and the other just spazzing out. Second, the extruder tended to jam in the middle of a print. Feliksdl promptly sent us a replacement extruder that had been tested, and we never ran into another jam.

The Felix is a pretty speedy machine. Its print quality is great when the belts and Z-leadscrew are properly tensioned and aligned. Aligning the Z-leadscrew is the hardest part of getting a great print; if it’s off, there will be ridges between the layers, known as Z wobble.

Retraction on the extruder is very good. There’s minimal stringing and you can probably get rid of it entirely by dialing in the PLA’s melting temperature.

The Felix was designed to print in PLA. While it has a heated bed, its open design doesn’t allow the bed to get hot enough to prevent ABS from warping (ours topped out at 75°C/167°F). The bed also needs to be slightly leveled every couple of prints, and it can warp due to the flexing of the aluminum.

Felix’s best feature is that it’s extremely quiet. DryLin polymer bushings glide along the linear rails so stealthily that even when the machine was “rapping,” there was hardly an increase of noise.

Update: *Felix 1.5 was announced during our review.* Orders from Oct. 1 ship with major upgrades, including:

- » Simpler extruder for quicker assembly, easier access to hot-end, and printing with rubber filament
- » Rigid ball-bearing linear rails by Hiwin for higher-precision prints
- » Motors with flats (no more filing!)

CONCLUSIONS

If you’re ready to build it, the Felix 1.0 is fast and quiet, with print quality on par with other machines, and better retraction and a bigger volume than most. But prepare for a true DIY experience.

HOW IT COMPARES

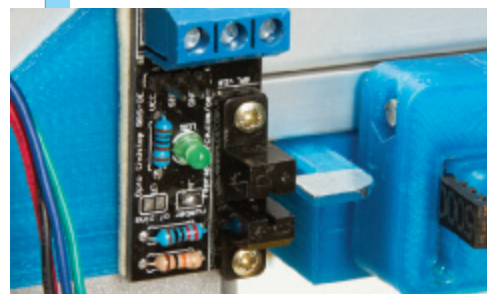
Kit Build	3/5
Setup	3/5
Documentation	4/5
Ease of Use	3/5
Hardware User Interface	1/5
Machine Software	3/5
Slicing Software	3/5
Speed	3/5
Reliability	3/5
Print Quality	3/5
Accuracy	4/5
Support/Overhangs	3/5
Noise	5/5
Value	3/5

PRO TIPS

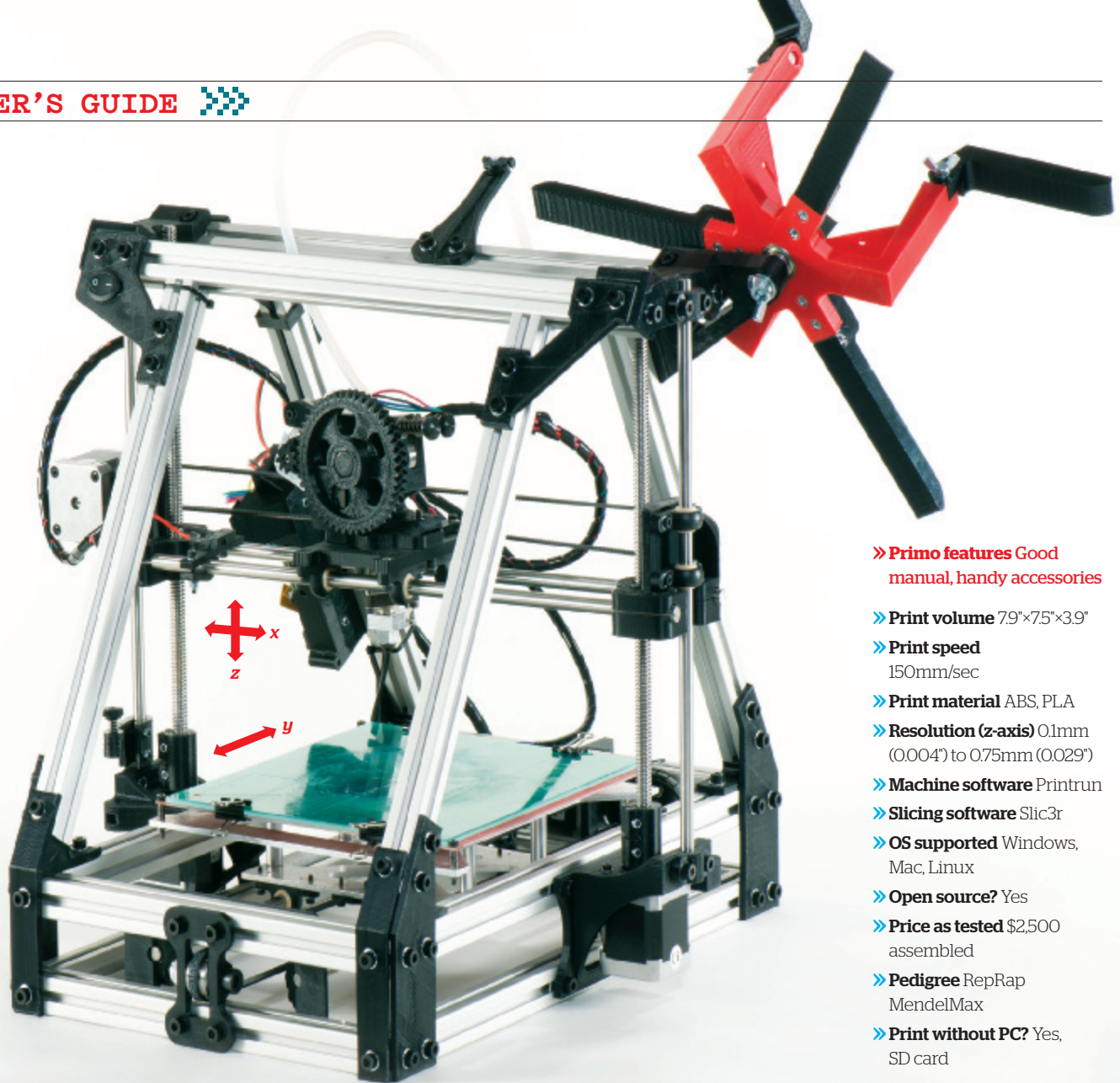
Print out these handy nut captures (thingiverse.com/thing:13807) for the three nuts on the bed leveling screws to make them adjustable by hand.

Mind the Z-leadscrew alignment to avoid visible Z wobble on your 3D prints.

THE DETAILS



Optical end-stops indicate their status with LEDs. DryLin polymer bushings on linear rails make the Felix ultra-quiet.



- » **Primo features** Good manual, handy accessories
- » **Print volume** 7.9"×7.5"×3.9"
- » **Print speed** 150mm/sec
- » **Print material** ABS, PLA
- » **Resolution (z-axis)** 0.1mm (0.004") to 0.75mm (0.029")
- » **Machine software** Printron
- » **Slicing software** Slic3r
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$2,500 assembled
- » **Pedigree** RepRap MendelMax
- » **Print without PC?** Yes, SD card

LulzBot AO-100

Aleph Objects lulzbot.com

Your basic MendelMax, with a better manual and accessories.

TESTED
BY
**CLIFF L.
BIFFLE**
AND
**LYRA
LEVIN**

WRITTEN
BY
**CLIFF L.
BIFFLE**

THE AO-100 IS ONE OF THE EASIEST WAYS TO GET A REPRAP MENDELMAX — it ships assembled, so setup is a simple matter of removing clamps and ties that protect the machine during shipping and plugging in a few cables. It also ships with a bunch of nozzles, knives, wrenches, and pliers, which is good because you might need to do some tweaking.

The AO-100 uses the same software as most open source printers we tested: Slic3r and Printron, which are neither beautiful nor intuitive. LulzBot provides copies on their website, along with downloadable settings files (hunt for the Downloads link, you'll eventually find them). Installation was reasonably painless. The manual recommended Linux, so we used an older Ubuntu 11.04 machine.

SETUP

The AO-100's manual says it's "pre-calibrated and tested." Unfortunately, as soon as we powered up the printer, it drove its extruder nozzle down into the platform and had to be powered off.

Like most printers, the AO-100 can't "feel" its nozzle touching the platform. Instead, it uses a separate switch on the side of its frame to know when to stop moving down — and the position of this switch is adjustable. The manual suggests a process for adjusting it, but we were surprised that it was so wrong out of the box. Once we'd adjusted it, we tried again — and the AO-100 drove its nozzle into a *different* part of the platform.

Like all printers derived from the RepRap Mendel, the AO-100 moves the extruder carriage up and down on two screws. If these screws get out of lock-step, the carriage is no longer level, and a good Z height on one side of the platform can mean a head crash on the other. This is rare during operation, but can happen if you accidentally turn one of the screws while the printer is off — something that's easy to do while adjusting the Z end-stop.

The manual provides no fix, so we devised one: bracing an SD card against each screw and cranking them down (by hand). With the end-stop height set and the carriage level, we got our first print on our third try.

Part of the AO-100's charm is its well-written color manual, way ahead of most of the competition. It's great for newcomers to 3D printing. But when the manual is wrong — we found a few places — or when the user goes beyond it, the going gets rough because while most printer manufacturers have a knowledge base on their site, LulzBot apparently doesn't. The software section of the manual is heavy on descriptions of each button, but light on directions for how to actually use the software.

PERFORMANCE

Once set up, the AO-100 is reasonably reliable. We cranked out a few fun items just by repeating the download-slice-print process; it never required manual nozzle positioning or adjustment. It does, however, require some regular maintenance:

» Managing the filament tension.

Two thumbscrews on the extruder must be adjusted together to set the filament tension. Too tight or too loose, and the feed may fail, ruining your print.

» Untangling the filament holder.

We had a print fail when the filament got pinched between the spool and the printer's frame. This meant we couldn't print without supervising it.

» **Taping the bed.** Tape must be periodically reapplied to the print surface. It's easy to mar, and if you print over a scar in the tape, it leaves a matching scar on your object.

The AO-100's SD card slot (combined with Printron) should have let us copy a model to the printer, hit Print, and walk away. We couldn't get this to work: the printer would halt unexpectedly and need to be power-cycled. (Since we had to supervise the filament spool anyway, leaving the computer plugged in wasn't a huge burden.)

With the factory settings, print quality was solidly middle-of-the-road. We spent an afternoon calibrating, but the greatest improvement was from simply lowering the printer's speed. While the LulzBot is capable of printing as fast as 200mm/sec, our tests indicate that quality suffers at high speeds. At 90mm/sec, small features often didn't cool before more plastic was extruded, resulting in a droopy appearance. At 40mm/sec, this was markedly reduced.

All objects came out a bit wobbly. This artifact was common on earlier RepRaps and the MakerBot Cupcake, but it's unusual on a Mendel; we weren't able to find the cause.

At \$2,500, the AO-100 costs more than some dual-nozzle printers like the MakerBot Replicator, and nearly twice as much as closed-source printers like the Afinia. In our tests, the output was notably worse than either of those printers.

CONCLUSIONS

The good: Factory assembled. Downloadable print settings worked right away. Comes with lots of plastic, accessories, and a well-written manual. The bad: Quality was midrange for a 2012 printer. Required significant tweaking and tuning. Price seems high. The ugly: The software.

HOW IT COMPARES

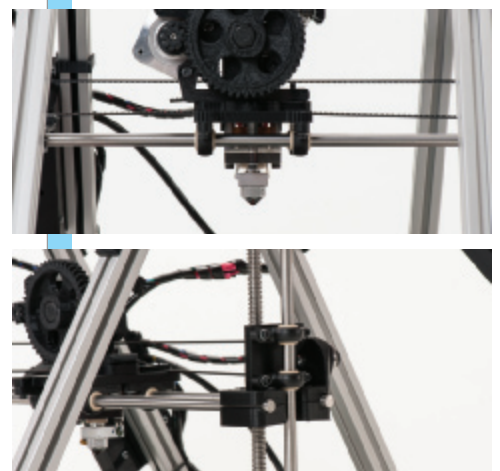
Setup	5/5
Documentation	4/5
Ease of Use	3/5
Hardware User Interface	3/5
Machine Software	3/5
Slicing Software	3/5
Speed	5/5
Reliability	5/5
Print Quality	3/5
Accuracy	4/5
Support/Overhangs	2/5
Noise	3/5
Value	2/5

PRO TIPS

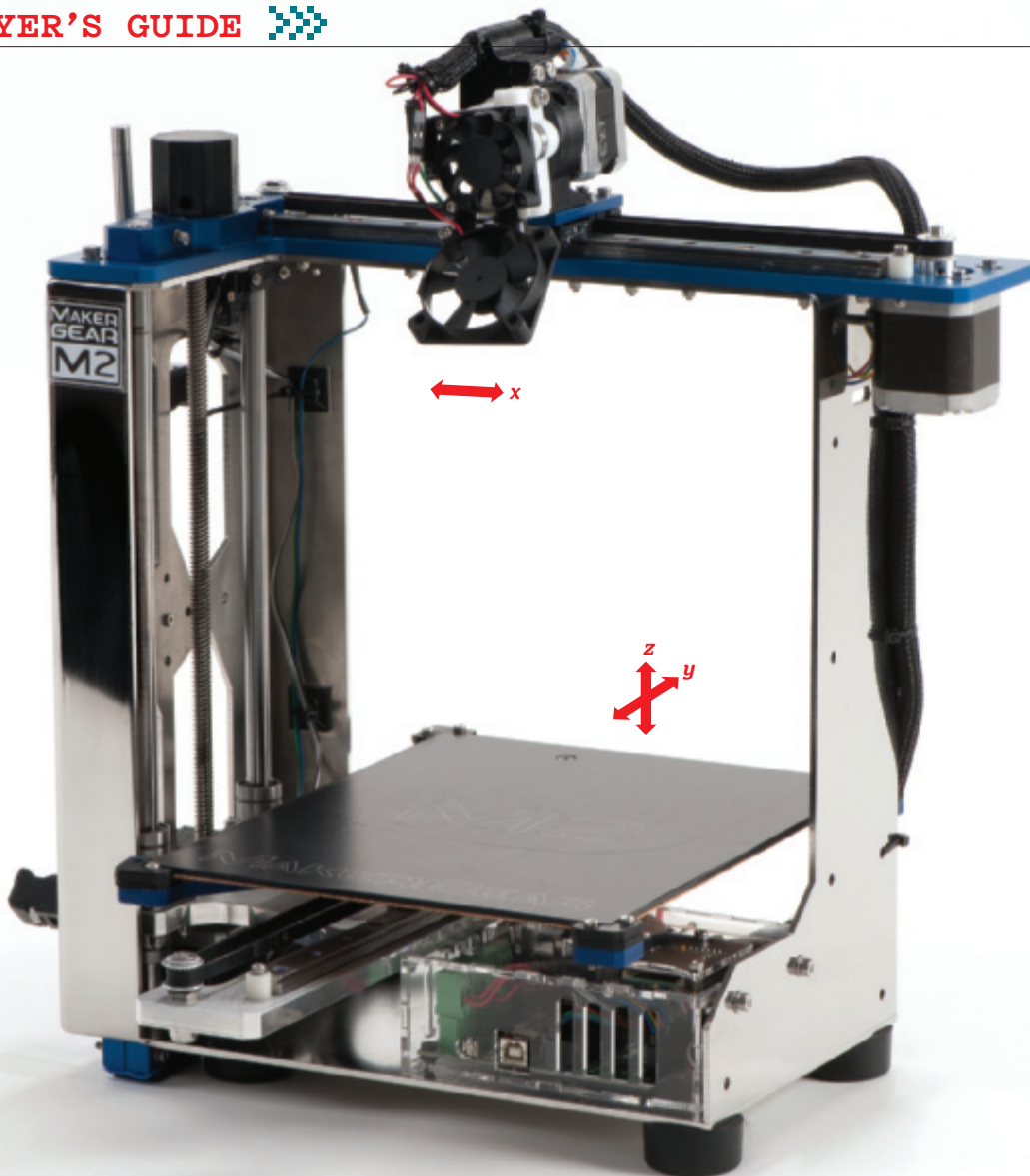
To speed turnaround, pre-warm a spare print bed on a hot plate. To even the heat, slip aluminum foil between the heater and the glass.

Dual extruders? Try R. Stillwell's modular aluminum X carriage. Bad filament feed? Print B. Phillips' spool arm and feed tube support. Files at makezine.com/3dprinting.

THE DETAILS



Derived from the RepRap MendelMax, the LulzBot AO-100 features the popular and reliable Budaschnozzle extruder, as well as 3D-printed parts bracing its frame and z-axis.



- » **Primo features** Metal construction, heated platform, polished frame, RAMBo mother-board, Teflon leadscrew
- » **Print volume** 8"×10"×8"
- » **Print speed** 150mm/sec
- » **Print material** ABS, PLA
- » **Resolution (z-axis)** 0.2mm (0.02mm possible)
- » **Machine software** Printron
- » **Slicing software** Slic3r
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$1,299 kit, \$1,499 assembled
- » **Pedigree** RepRap Mendel/Prusa
- » **Print without PC?** Yes, SD card

MakerGear M2

makergear.com

Steel-solid, big volume, prints great – with tweaking, the M2 could be best-in-class.

TESTED
AND
REVIEWED
BY
**PAUL
LEONARD**

MAKERGEAR'S M2 IS THE LONG-AWAITED FOLLOWUP to their Mosaic 3D printer, and while there is a family resemblance, there's been a radical upgrade. Forget plywood — this printer's frame is stainless steel, and the rest of the structural elements are stainless and anodized aluminum. The print volume has also been greatly expanded to 8"×10"×8" — one of the biggest in its price range.

The x- and y-axes are built with precision linear rail operated by 2GT belts with aluminum pulleys. The z-axis is two hefty rails of precision-ground shafting actuated by a Teflon-coated Acme leadscrew mounted directly into the Z stepper motor. As a result of these premium parts, the motion is very smooth.

The extruder is MakerGear's geared stepper motor-based design, with their groove-mount hot end. The M2 ships with a 0.35mm nozzle, but other sizes are available. The heated build platform is a sandwich of cork insulation, polyamide heating element, and laser-engraved aluminum, topped off with a sheet of borosilicate glass. It's all pre-wired; just plug in the heater and thermistor.

The control electronics package is UltiMachine's latest RAMBo board, a refinement of the common RAMPS package, all on one board. RAMBo supports dual extruders, so MakerGear (or you) might upgrade the printer to a dual-extruder setup in the future without having to replace the electronics.

KIT OR ASSEMBLED?

Unable to obtain a printer in time for the test weekend, MAKE invited me to review mine, which I purchased as a kit for \$1,299. I recommend buying it fully assembled for \$1,499; it's a small price to pay for the hours you'd spend (and the worry of something going wrong).

The kit is very well organized and includes every tool you need except an adjustable wrench. Kit documentation is very nice — animated videos, sub-assembly drawings, explicit instructions for critical steps — but also has confusing gaps. Questions were answered promptly by MakerGear tech support on IRC.

During my build I discovered that my z-axis platform wasn't traveling smoothly through its full range. MakerGear determined that the frame was welded out of square. They promptly replaced it and returned my M2 fully assembled. From my discussions with other M2 owners it seems this was an isolated instance.

SETUP

Setup is simple: you can unpack, adjust the stops, load the software, and start printing the included samples in less than an hour. Find a sturdy table — the M2's metal construction makes it reassuringly heavy, and when it operates at higher speeds it will shake things around.

Installing Printron/Pronterface and Slic3r is straightforward, and you can choose other software packages if you wish. I have yet to modify the firmware

for the electronics; that will require the Arduino environment and downloadable Marlin firmware that's been tweaked for RAMBo support. Links to all these tools are on MakerGear's M2 wiki page.

The M2 ships with an SD card reader and a card loaded with sample G-code files to verify that your printer is working and hasn't been damaged in transit. They also include a 1kg spool of PLA filament.

Still, there's a learning curve. Before you print, peruse MakerGear's Google Groups for tips on how to level the bed and adjust temperatures for different plastics and bed surfaces (MakerGear should put these in their documentation), and learn about the settings and options available when printing. MakerGear has taken some of the sting out of this by shipping it pretty well calibrated.

PERFORMANCE

Once I got the Z end-stop positioned correctly and the bed leveled, the M2 printed really well. The hot end got up to the set temperature quickly and remained stable; there's a method for tuning the temperature control in the firmware, but it's very good without any tinkering. The heated bed worked great too.

Out of the box I'm getting better prints than I ever got from the communal RepRap Prusa-ish bot down at my hackerspace: sharp corners and overhangs, accurate dimensions, clean and true surfaces. The MakerGear wiki provides really good default settings for Slic3r.

I've been experimenting with different layer heights, speeds, and temperatures, and I don't think I've come near the M2's full capabilities. Not only can I improve the software settings to get even better output, but because the machine can accommodate improvements in extrusion technology, I'll also be able to expand and upgrade my M2 for a long time to come.

CONCLUSIONS

For quality, service, and value, it's hard to find a better DIY desktop 3D printer than the MakerGear M2. The structure is very rigid, the linear motion components second to none. The M2 is capable of producing high-quality prints straight out of the box — with the potential to improve to best-in-class with a little tweaking.

HOW IT COMPARES

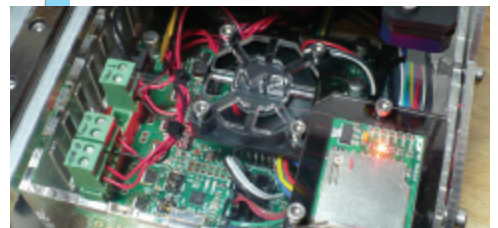
Kit Build	4/5
Setup	4/5
Documentation	4/5
Ease of Use	4/5
Hardware User Interface	3/5
Machine Software	3/5
Slicing Software	3/5
Speed	4/5
Reliability.....	4/5
Print Quality	5/5
Accuracy	5/5
Support/Overhangs	5/5
Noise	2/5
Value	4/5

PRO TIPS

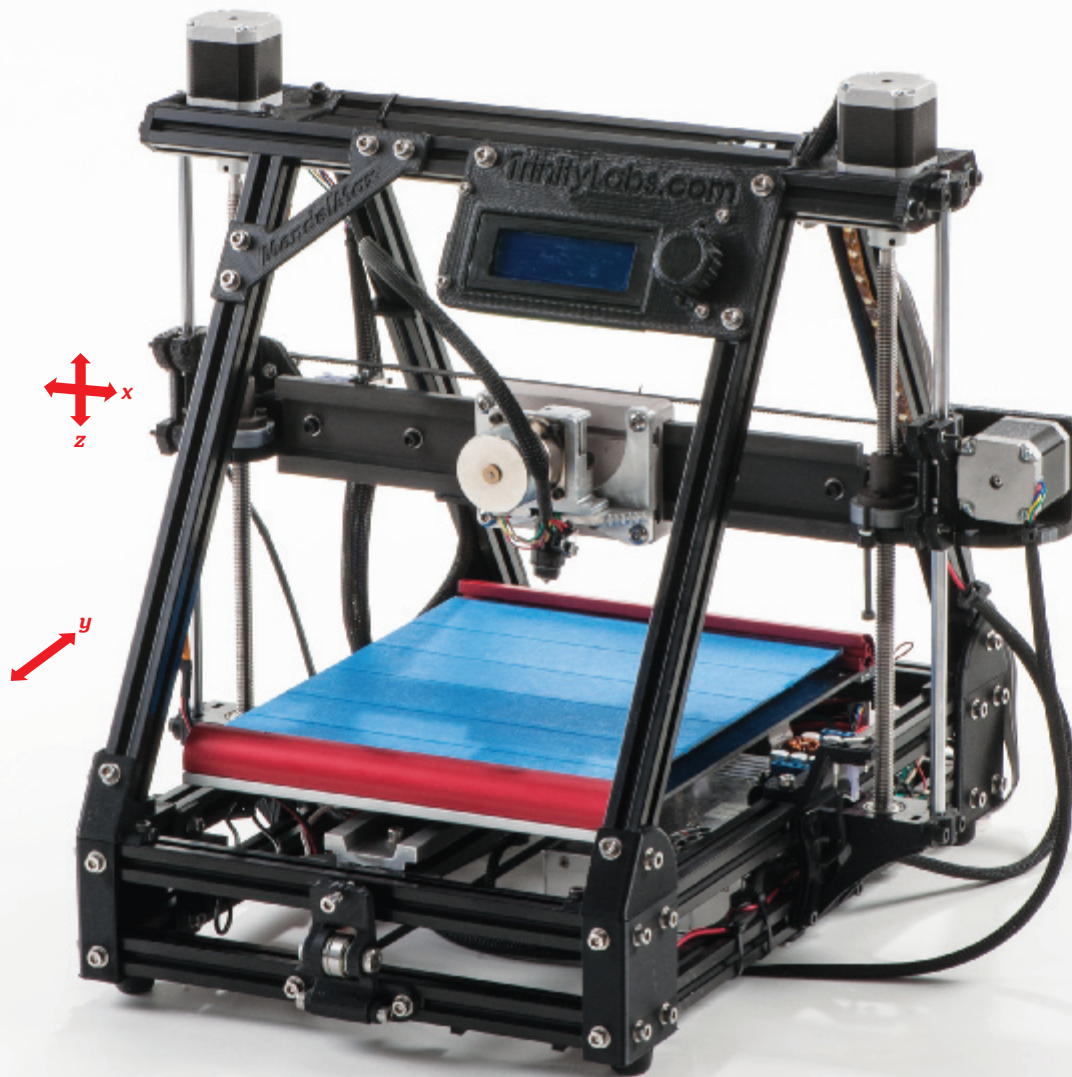
Check MakerGear's Google Groups for calibration tips before doing those first prints!

Don't be afraid to go into the IRC chat and ask questions. There's nearly always someone there, either from MakerGear or just users, and they're all happy to share their experiences and help you get your best prints.

THE DETAILS



With premium linear motion components and the latest all-in-one motherboard, the M2 is one high-quality machine.



- » **Primo features** 200W glass build platform heats up fast, high-grade linear motion components, LED backlighting, LCD user interface
- » **Print volume** 9"×10"×7"
- » **Print speed** Very fast, +150mm/sec
- » **Print material** PLA, ABS, PVA
- » **Resolution (z-axis)** 0.32mm-0.3mm
- » **Machine software** Pronterface
- » **Slicing software** Slic3r
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$1,295
- » **Pedigree** RepRap MendelMax
- » **Print without PC?** Optional, SD card

MendelMaxPro

Trinity Labs trinitylabs.com

This professional-grade printer is a cut above its kin, but is it ready for your living room?

TESTED
AND
REVIEWED
BY
**MATT
GRIFFIN**

THE TRINITY LABS MENDELMAXPRO IS ONE OF A RECENT SPATE OF "RETAIL REPRAP" PRINTERS (see the Lulzbot AO-100, page 52), but this unit has two great things going for it. First, it's the newest in its class, so it benefits from "standing on the shoulders" of earlier efforts. Second, founder Ezra Zygmuntowicz has extensive experience with the MendelMax, having built countless versions before developing this one as a product.

Trinity Labs has reimagined the MendelMax as a tool for the assembly line: think industrial sliders, cable management, worklights, and service access. It's a machine meant for tech startup backroom production, but is this affordable "professional model" ready for wide release?

The MendelMaxPro has a macho, aerospace-grade look, like it's ready for

deep-sea trawling or powering a winch to rescue your Dodge Ram out of a bog. Counter to appearances, the fine-looking Misumi structural beams represent a cost savings over the traditional RepRap threaded rods and components. Each element was carefully sourced, and many extra features came about because the designer located high-grade components closer to hobby price points. We tested a prototype before customer release, so it was more sensitive than you'd expect.

Trinity Labs did a solid job redesigning elements of the MendelMax, replacing less-reliable parts necessary for "true RepRap" self-replication with industrial solutions. Most notably, they replaced the rods and bearings in the Cartesian gantry — subject to wear and drifting out of spec — with industrial sliders that give confidence the machine will hit its marks after hundreds of hours of use.

The team also sourced an excellent pair of precision drive and smooth guide rods for the z-axis that let them eliminate the redundant z-axis riders typical of Mendels, a primary risk of over-constraint and binding. Professional-grade couplers for the threaded rods help maintain integrity at high speeds.

The custom-milled extruder has a pair of hobbled drive and idler gears that allow for fast, precise shifts between extruding and retracting without filament slippage. Folded aluminum braces clamp a heavy glass build plate suitable for printing in various materials. Underneath the glass, a heater board with super-fat traces provides steady heat for printing in ABS.

An LCD screen provides status updates, while strips of LEDs illuminate the entire work area nicely.

SETUP

Customers will receive one hour of tech support with each machine, but we didn't utilize our full hour (we should have). After installing Pronterface and the custom Slic3r profile provided by Trinity Labs, we were able to quickly generate a model and connect to the machine. (The documentation, which is a work in progress, lacked instructions for using the SD card interface.)

The machine required very little tweaking to set up auto-homing — just rotate

the drive rods with the stepper motor disengaged until the extruder nozzle can trace a parallel path across the build platform, then adjust a bolt on the x-axis side bracket that triggers the end-stop to establish Omm layer height. We had no trouble starting a print and monitoring its temperature and progress in Pronterface.

PERFORMANCE

For a machine known for its high speed, I was surprised to encounter adhesion problems until I read a suggestion in the documentation that I'd overlooked: paint a light smear of an ABS-and-acetone slurry onto the glass first. This solution worked well, though it made me less excited about having the MendelMaxPro printing in my living room.

Disappointingly, the Slic3r profile — combined with my first-time operator skills — delivered lackluster results when printing the snake and the torture-test object. Horizontal surfaces were true, but verticals were not smooth and the top caps of each part were more of an open mesh. Trinity Labs customer support suggested turning off extruder "hopping" — a professional 3D printer strategy for lifting up and touching back down that allows for very fast travel — and the sides of the snake, in particular, were improved. The owl model, printed with infill, wasn't as clean as that of many other printers.

Clearly the default Slic3r profile needs tweaking, but I suspect the real issue is calibrating the machine. While it was easy to get it up and running, I think really dialing it in would take that entire hour of one-on-one dedicated care. The benefits of careful tweaking are probably well worth it: this is a machine designed for high speeds and high repeatability.

CONCLUSIONS

When casting the role of battle-tank printer in your entrepreneurial tech product venture, look no further: the MendelMaxPro is designed to impress. Home users should wait for complete documentation and calibration procedures to overcome the early-batch kinks. Clearly the potential is there; Trinity Labs uses MendelMaxPro machines to churn out 3D-printed parts for this and other products, and they look great.

HOW IT COMPARES

Setup	4/5
Documentation	4/5
Ease of Use	4/5
Hardware User Interface	5/5
Machine Software	3/5
Slicing Software	3/5
Speed	5/5
Reliability	4/5
Print Quality	3/5
Accuracy	2/5
Support/Overhangs	4/5
Noise	2/5
Value	4/5

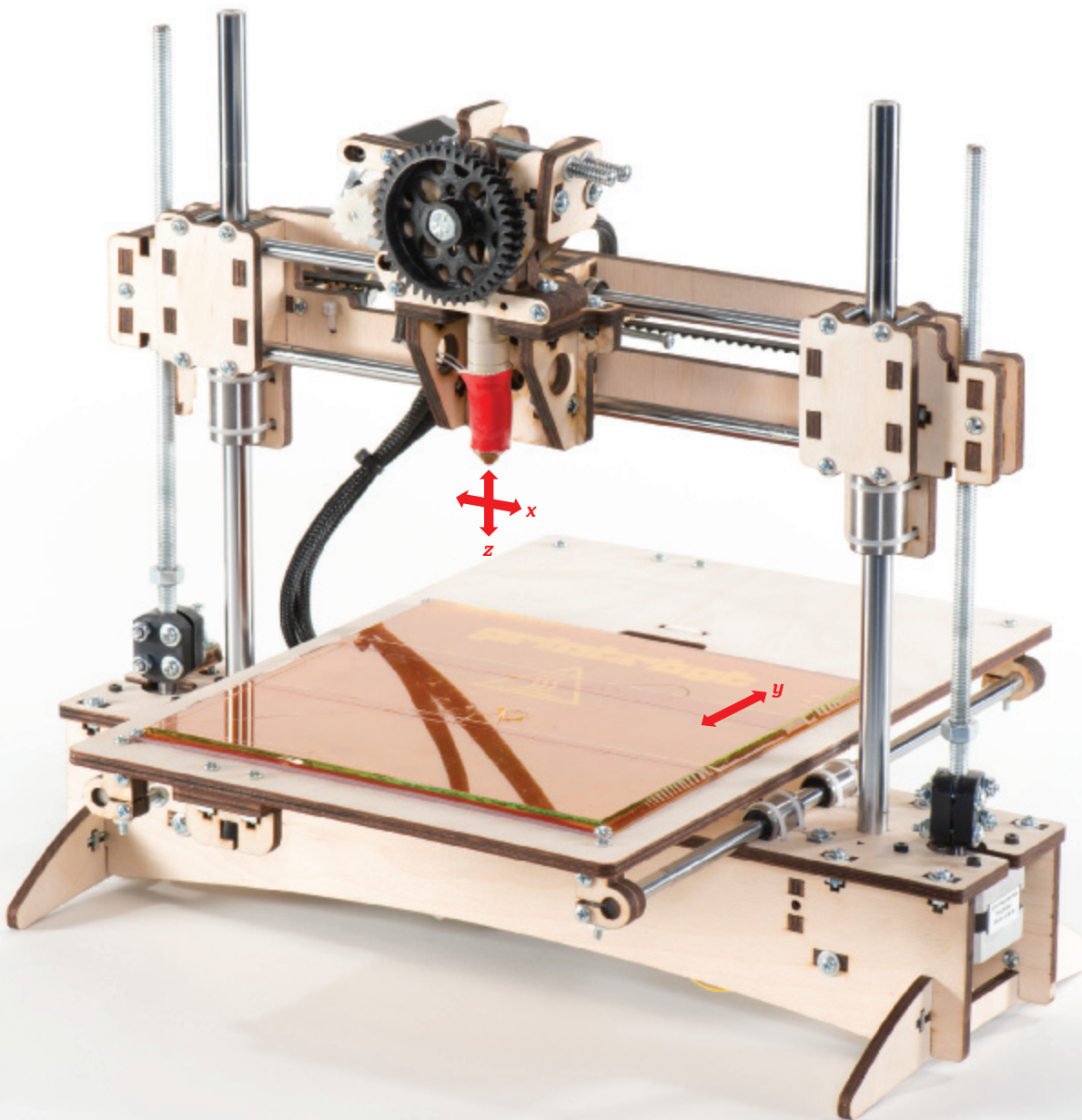
PRO TIPS

With Mendel-breed machines, the z-axis uprights can bind on the rods if the extruder slips out of parallel. To improve performance, loosen the z-axis guide brackets, tilt the extruder arm until the nozzle's path is perfectly parallel to the plate, then run the z-axis up and down for a while to "wear in" the machine. Now you can tighten the guides to hold this position, without introducing binding.

THE DETAILS



Pro grade: With a custom-milled precision extruder, LED lighting, and industrial-grade sliders on the x- and y-axes, this machine is a cut above its MendelMaxian kin.



- » **Primo features**
Extendable in any axis, heated print bed, SD card slot
- » **Print volume** 6"×6"×6"
- » **Print speed** Up to 200mm/sec
- » **Print material** ABS, PLA
- » **Resolution (z-axis)** 0.4mm-0.1mm
- » **Machine software** Printron/Pronterface
- » **Slicing software** Slic3r, Skeinforge
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$799 assembled
- » **Pedigree** Original
- » **Print without PC?** Yes, SD card

Printrbot LC

printrbot.com

For the tech-savvy, Printrbot offers expandability, speed, and acceptable prints at a reasonable price.

WRITTEN
BY
**BLAKE
MALOOF**

TESTED
BY
**BLAKE
MALOOF
AND
EMMANUEL
MOTA**

THE PRINTRBOT IS A RELATIVE NEWCOMER to the field of consumer-grade 3D printers and is touted by its creator, Brook Drumm, as "your first 3D printer." After a wildly successful Kickstarter campaign in December 2011, where they received over \$800,000 in funding, Printrbot has been working to develop low-cost printers that can maintain quality while

increasing portability. They've produced a few different models to suit a variety of user needs, from the Printrbot Plus with its 8"x8"x8" print volume, to the compactable Printrbot Jr. (reviewed on page 60).

We tested the Printrbot LC, with a laser-cut plywood frame, a print volume of 6"x6"x6", and a heated bed for ABS printing. The LC sells for the save-your-lunch-money price of \$799 assembled, \$549 as a kit.

Unlike many 3D printers, which have a box or an enclosed case around the bed and extruder, the Printrbot features an open frame design that makes it compact (16"x16"x16"), light (only 18lbs), and most importantly, extendable. All printing axes can be modified to create a larger build volume, making the Printrbot (and its relative, the new Bukobot, see page 46) the most flexible 3D printer we've seen on the market. The manufacturer reports Printrbots being extended over 2 feet in height, and others featuring a double-wide base of 16"x8". So not only is a Printrbot a great machine for getting your feet wet with home 3D printing, it can also be expanded once you've outgrown your 6" build platform.

One trick the Printrbot employs to keep its desktop footprint so small is separating the power supply from the body of the printer itself. Perched on top of the power enclosure, the cleverly designed spool reel sits on casters and feeds filament to the extruder. We encountered no kinking or snags in the spooling mechanism in our tests, and the simplicity of its design makes other solutions seem needlessly over-engineered.

The LC also features an SD card slot on the back, which allows you to unplug your computer while it prints from the card.

SETUP

The Printrbot connects to a Mac or PC via USB cable and uses the popular open source print interface Pronterface. While this software has a slight learning curve, Printrbot's getting-started guide tells you what you need to know to calibrate the machine and the software for your first print.

Within a half-hour we were able to calibrate the Printrbot and send it a sliced

3D model, and it was on its way.

PERFORMANCE

The final prints won't win any awards for high resolution or vertical smoothness, but the results are certainly acceptable for such an inexpensive printer.

Overhang tests caused some issues with noticeable buckling, and curved surfaces showed visible stair-stepping, but layer height remained consistent and proportions turned out to be fairly precise. In tall vertical surfaces, some rippling could be seen, but the overall form of the prints was solid and reasonably accurate. We did wish for a cleaner print of our nautilus gears; they reminded us that the larger Printrbot Plus (\$699 kit, \$949 assembled) has beefier smooth guide rods that help with stability.

On the plus side, out of the box the Printrbot LC was relatively speedy compared to other machines, and with modification it can be made even faster. According to the manufacturer tweaked-out Printrbots can get up to 200mm/sec.

CONCLUSIONS

If you're new to 3D printing but relatively tech-savvy, the Printrbot LC is a good and reasonably priced introduction to this fascinating emerging technology.

It comes assembled, requires a little calibration, and requires you to familiarize yourself with the software interface, but once you're up and running, you can hit Print and let it run without needing to futz too much. And if you're feeling adventurous, you can tweak and upgrade it to print larger, faster, and in higher detail so your inexpensive, compact little machine can compete with the quality of higher-priced units.

HOW IT COMPARES

Setup	4/5
Documentation	4/5
Ease of Use	3/5
Hardware User Interface	3/5
Machine Software	3/5
Slicing Software	3/5
Speed	4/5
Reliability.....	3/5
Print Quality	3/5
Accuracy	3/5
Support/Overhangs	3/5
Noise	3/5
Value	4/5

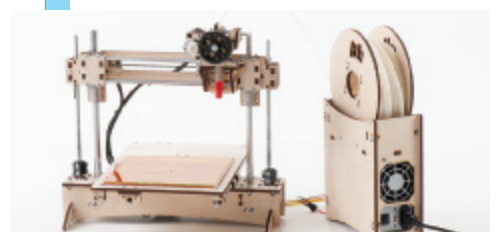
PRO TIPS

Make sure the printed gears for the motor are secure. It'll save you taking apart your new printer.

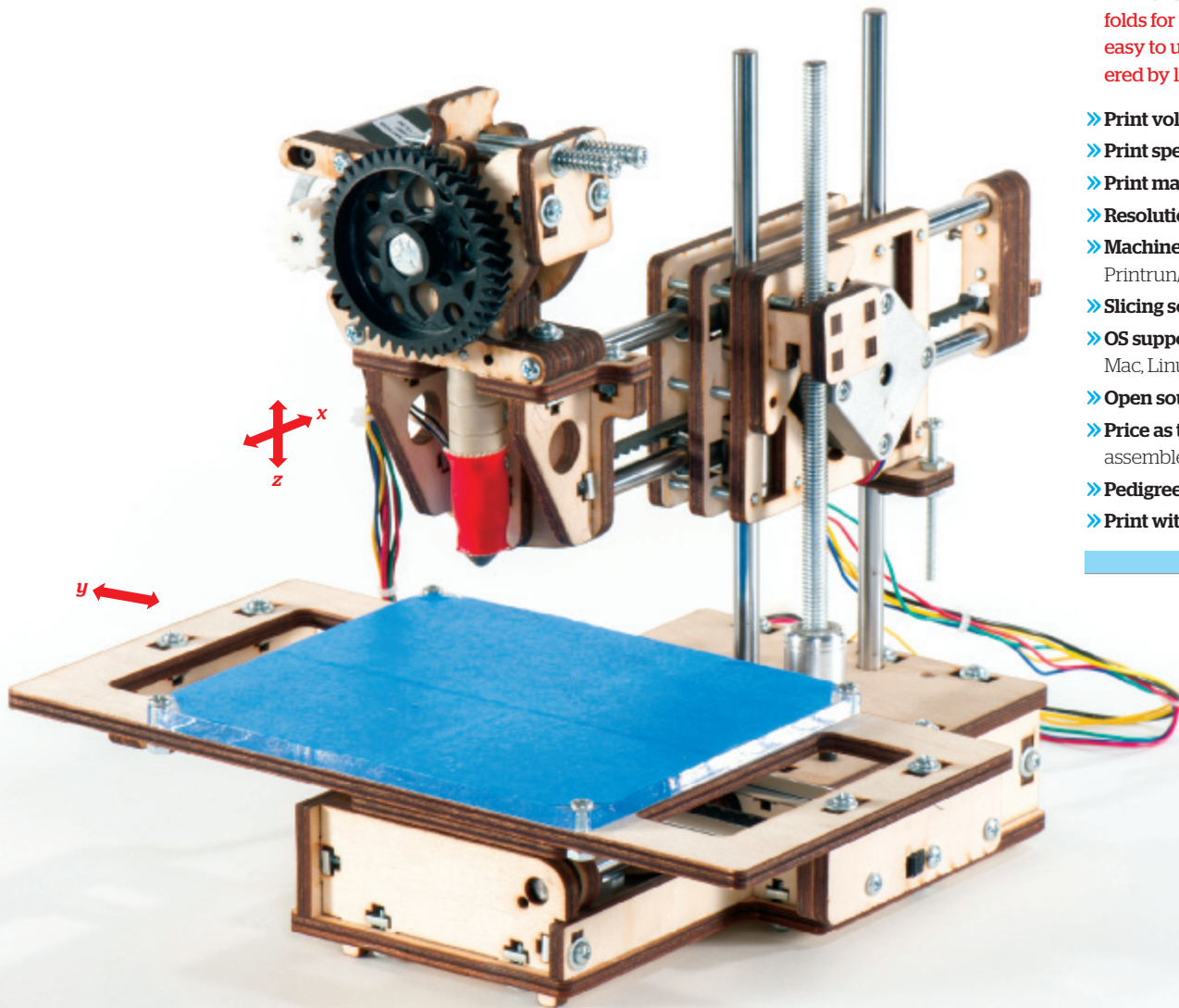
Add a funneled fan to make your prints even cleaner.

In Pronterface, extrude filament for 30 seconds to see how it feeds. Then adjust your spool to make sure filament spools off evenly.

THE DETAILS



Mounting the filament spool on the power supply is a simple but effective solution. You can choose to print from an SD card and, once started, unplug your computer while the Printrbot keeps printing.



» **Primo features** Compact, folds for portability, very easy to use, can be powered by lithium battery

- » **Print volume** 4"×4"×4"
- » **Print speed** 100mm/sec
- » **Print material** PLA
- » **Resolution (z-axis)** 0.1mm
- » **Machine software** Printron/Pronterface
- » **Slicing software** Slic3r
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$399 assembled
- » **Pedigree** Original
- » **Print without PC?** No

Printrbot Jr.

printrbot.com

Surprisingly good prints from the cheapest, smallest, most portable 3D printer yet.

WRITTEN BY
 LYRA LEVIN,
 AND MATT GRIFFIN

TESTED BY
 LYRA LEVIN,
 CLIFF L. BIFFLE,
 EMMANUEL MOTA,
 AND BLAKE MALOOF

BROOK DRUMM'S PRINTRBOT JR. IS THE FIRST OF WHAT WILL BE A SERIES OF "PORTABLE PRINTRBOTS" designed for those exploring 3D printing for the first time. (Also in this series: the briefcase printer created in collaboration with designer Ben Heck, PrintrbotGO, that was demonstrated at World Maker Faire 2012.)

By far the tiniest and least expensive 3D printer on the market, the Jr. is a baby-scale version of the original Printrbot. (Some of the other printers in our test could probably print a full-scale model of the Printrbot Jr. in one go.) But this pint-sized, PLA-only printer borrows enough of its bones from its parents,

and adds enough unique special features, to be a better experience than just “My First 3D Printer!”™”

When fully open, the diminutive machine fits easily on a corner of your desk, and most of its footprint is the 4"×4"×4" printing volume. When folded for travel, a good third of the volume is packed in, with most of the fiddly bits protected by the bed. It easily slips into a backpack, a theory we proved both before and after our test.

The unit comes with a standard, inexpensive PC ATX power supply, and the vendor provided us with a premium add-on — a laser-cut enclosure for the PSU that does double duty as a filament spool holder.

But there’s another option for power, unique to this machine: using a rechargeable lithium polymer (LiPo) battery as an optional add-on to supply power when printing in the field. We ran some of our final test prints using a LiPo quadcopter battery (warning: soldering required), and were amazed to realize we could just as easily be printing them on top of a mountain somewhere.

We began our test with the Jr. Beta, which was replaced with the final Jr. release before we had the opportunity to print all the test pieces. Thus we were able to observe improvements in the released model, most notably a process for leveling the platform by tightening it down on compression springs, and adjustments to the laser-cut folding parts to allow for pretty much one-handed flipping down and closing up of the build platform.

Simplicity is a design feature for this printer, and while it ships assembled, videos of Drumm quickly disassembling and reassembling the unit demonstrate how carefully the machine has been reduced to the fewest moving parts possible. In his quest for simplicity, however, Drumm sacrificed some bells and whistles: the Jr. prints only PLA, doesn’t have a heated platform or a fan, and has a simplified gantry system.

SETUP

At the time of our test, documentation for setup, calibration, and use were absent. Thankfully, the steps were rela-

tively standard (some identical to the original Printrbot, whose instructions are on the vendor’s site).

By following the grown-up Printrbot’s instructions, we were able to set up the software and print our “Christmas morning” test fairly quickly. Links to the recommended software (Slic3r and Pronterface) are in the Instructions page on the Printrbot website. Having already installed and played with these with other printers, we already knew the standard run-time procedure.

We used the slicing profile Drumm included with the unit to prepare the parts for printing.

PERFORMANCE

For a \$400 assembled printer, the print test results were tremendously better than expected.

The first prints we rolled off the Jr. were officially “not bad.” Following these, we took time to carefully level the platform by eye, running the nozzle horizontally across the plate to make sure the path was parallel.

The torture test printed decently on a third attempt, but the slicing profile was perhaps too conservative in terms of layer height, so the results were coarse; and the printer extruded more plastic than necessary, resulting in constrained bolt holes and runny vertical features.

The printed nautilus gears worked immediately upon assembly, showing off the Jr.’s ability to print thin, stable walls. Though the prints suffered from common problems such as not capping the top of horizontal flats and low resolution, they were certainly as good or better than some of the \$1,000-and-up machines.

CONCLUSIONS

Definite perks of the Printrbot Jr. are its size and price: it’s the most portable 3D printer on the market, and priced at only \$400 it’s within reach of hobbyists, students, and other casual users.

Plus it seems likely that the Jr.’s open source hardware and software will arm a dedicated community with the tools necessary to tweak and improve this simple unit so that power users can achieve results comparable to far more expensive and beefy machines.

HOW IT COMPARES

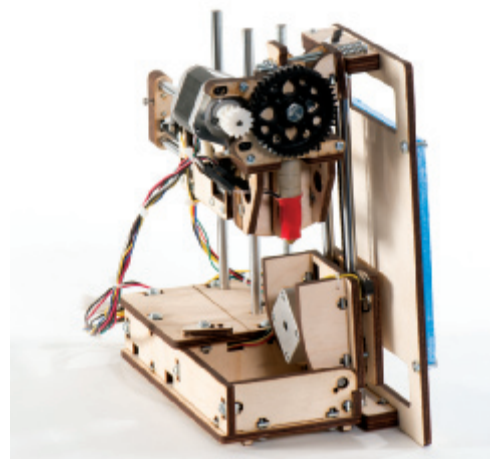
Setup	4/5
Documentation	2/5
Ease of Use	5/5
Hardware User Interface.....	3/5
Machine Software	3/5
Slicing Software	3/5
Speed	4/5
Reliability	4/5
Print Quality	4/5
Accuracy	3/5
Support/Overhangs	3/5
Noise	4/5
Value	5/5

PRO TIPS

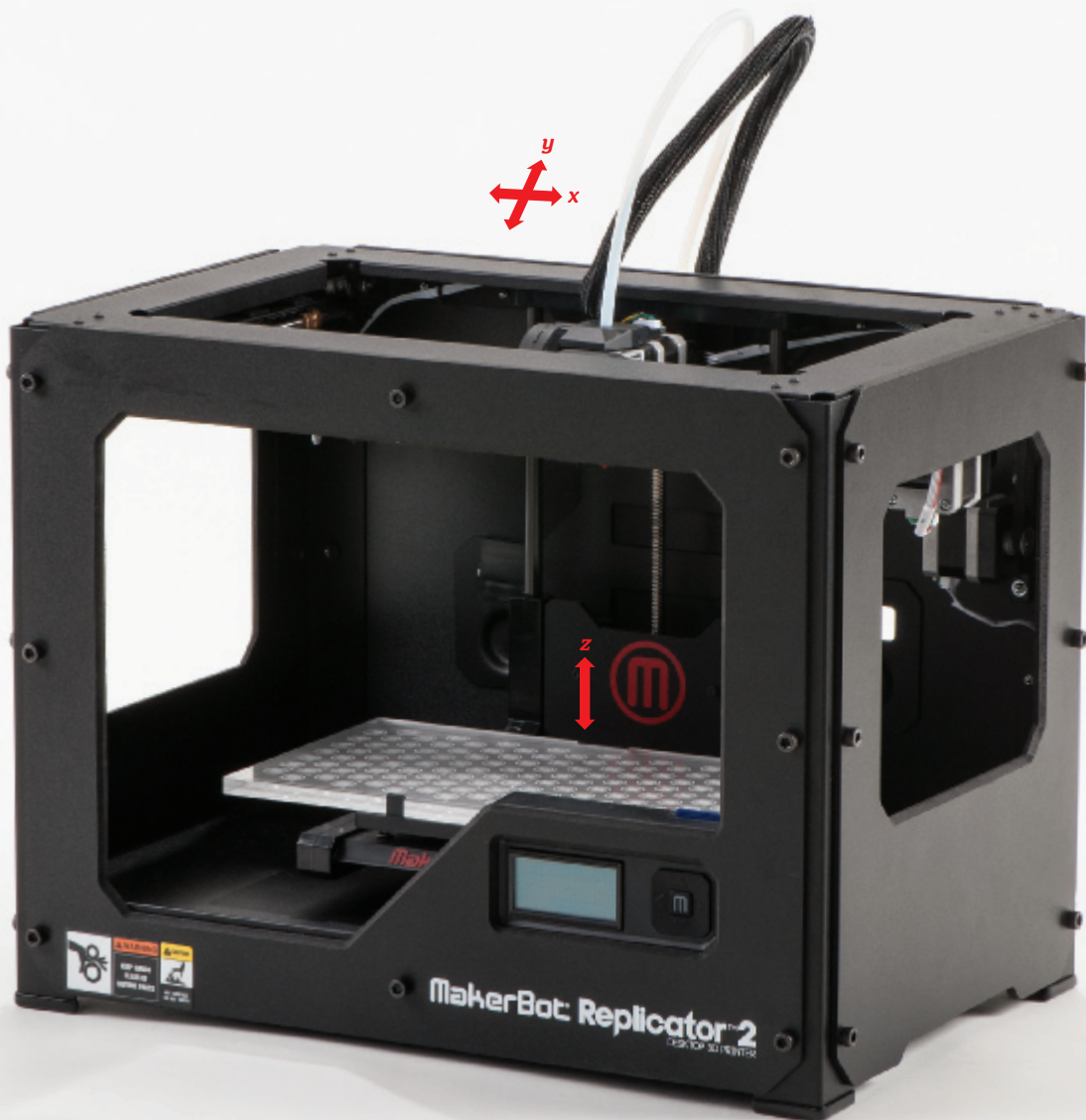
You’ll need to connect the stepper motors to the control board. Watch the assembly videos and patch the cables into the correct ports; otherwise you can damage your printer.

Get a roll of 3M ScotchBlue Painter’s Tape Original Multi-Surface 2090, from any hardware store, for covering the print bed.

THE DETAILS



Not only does this tiny printer perform as well as machines costing three times more, it’s also the most compact, it folds up to be even smaller for portability — and it can even run on a quadcopter battery.



- » **Primo features** LCD control panel, cold pause, paper-thin layer heights
- » **Print volume** 11.2"×6"×6.1"
- » **Print speed** 80-100mm/sec
- » **Print material** PLA
- » **Resolution (z-axis)** 0.10mm-0.34mm
- » **Machine software** MakerWare
- » **Slicing software** MakerWare
- » **OS supported** Windows, Mac, Linux
- » **Open source?** No
- » **Price as tested** \$2,199
- » **Pedigree** MakerBot Replicator
- » **Print without PC?** Yes, SD card

Replicator 2

MakerBot Industries makerbot.com

No longer open source, the Replicator 2 nevertheless impresses with major upgrades.

TESTED
BY
**EMMANUEL
MOTA
AND
ERIC
WEINHOFFER**

WRITTEN
BY
**EMMANUEL
MOTA**

THE REPLICATOR 2 IS THE NEWEST ITERATION OF MAKERBOT'S wildly popular Replicator. Now faster, quieter, and with a paper-thin 100-micron minimum layer height, the Replicator 2 is worthy of its 2.0 badge. It sports a new steel frame, oil-impregnated bronze linear bearings, and a 37% larger build volume, and it's optimized for PLA.

The upgrades make what was already a fantastic machine even better — but a higher price and a departure from the open source platform may impact MakerBot's current popularity with makers. The Replicator 2 single-extruder PLA-only model that we tested costs \$2,199. The Replicator 2X dual-extruder

ABS/PLA model (scheduled for early 2013 release) will set you back \$2,795. Another \$350 gets you a 1-year “MakerCare” warranty on electronics and mechanical components.

The Replicator 2 has a sleek modern look with an all-black powder-coated steel frame and new PVC side panels that are removable, customizable, and shaped to allow easy cleaning of any excess material that falls from the build platform. The machine has kept the same overall footprint and basic design while enlarging the build volume. A larger, more responsive LCD panel with keypad on the front right corner allows for easy control and monitoring of the machine.

A highlight is the new Cold Pause feature that pauses the print, cools the extruder, and waits for you to resume where you left off, which could come in handy in more than a few situations.

Another fun, though perhaps less useful, function of the keypad is the ability to select the color of the interior LED lighting to suit your mood. The build area of the Replicator 2 is now inhabited by a quick-release, frosted acrylic bed specifically made for use with PLA (polylactic acid) plastic. PLA is a corn-based, biodegradable, and sustainable medium for 3D printing that has a lower melting point than ABS plastic and doesn't require a heated bed, so it uses 32% less energy to print.

SETUP

Without the need to wait for a heated bed, the Replicator 2's warm-up time to start a print is much shorter than MakerBot's previous ABS-printing models.

Print bed leveling is also easier, thanks to the new three-point bed leveling system. Instead of four adjustment screws, one in each corner of the bed, three screws are arranged in a triangular shape, widening the center point; a twist of two screws can quickly level the bed. These two features make preparation time quicker and more straightforward.

The upgraded features on the machine are complemented by brand-new software. MakerBot's new MakerWare replaces the open source ReplicatorG, with a cleaner and more intuitive user interface that lets you scale, rotate,

and arrange multiple STL models on the build platform with ease. Slicing for medium and low resolution settings is now performed by the Miracle-Grue engine within MakerWare, significantly faster than Skeinforge, which is still used for high-resolution printing.

The sliced model is loaded onto an SD card (included) and inserted into the Replicator 2. Then you just hit Print and sit back and watch (or not). The use of the SD card, carried over from the original Replicator, frees you from having a computer tethered to the machine for the duration of the print.

The Replicator 2's initial setup, out-of-box to first print, was simple and quick — it took us less than 15 minutes, including attaching the extruder and loading the filament. MakerBot pre-leveled the bed for us; that might take you an extra five.

PERFORMANCE

The Replicator 2 produced consistently attractive prints and is capable of layer heights as fine as 0.1 millimeters (100 microns). Capping is visibly improved over the original Replicator, leaving our owl test print with a smooth, round top.

Our test machine did show minor signs of under-retraction, leaving a small line of extra material on some prints, though this may have been particular to our machine, which was not a final production model.

The Replicator 2 failed to produce the arch in our torture-test print, though few printers succeeded at this feat.

Another much-appreciated improvement: reduced noise. The Replicator 2 was noticeably quieter thanks to its new self-lubricating, oil-impregnated brass linear bearings. Setting the printer on carpet reduced the machine noise to only the whir of the extruder's fan.

CONCLUSIONS

The Replicator 2 is a definite improvement over the original. Print quality is comparable to other machines in our test, but the new software is a real upgrade, and the hardware improvements make the machine more dependable, sturdy, and consistent, with a larger build size, faster print times, and quieter running. The new look is a welcome addition too.

HOW IT COMPARES

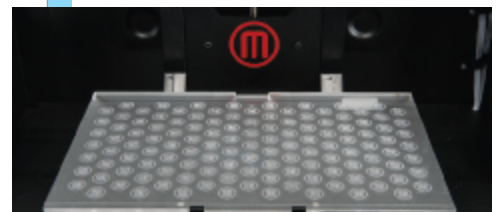
Setup	4/5
Documentation	4/5
Ease of Use	5/5
Hardware User Interface	5/5
Machine Software	4/5
Slicing Software	4/5
Speed	4/5
Reliability	4/5
Print Quality	4/5
Accuracy	4/5
Support/Overhangs	5/5
Noise	5/5
Value	3/5

PRO TIPS

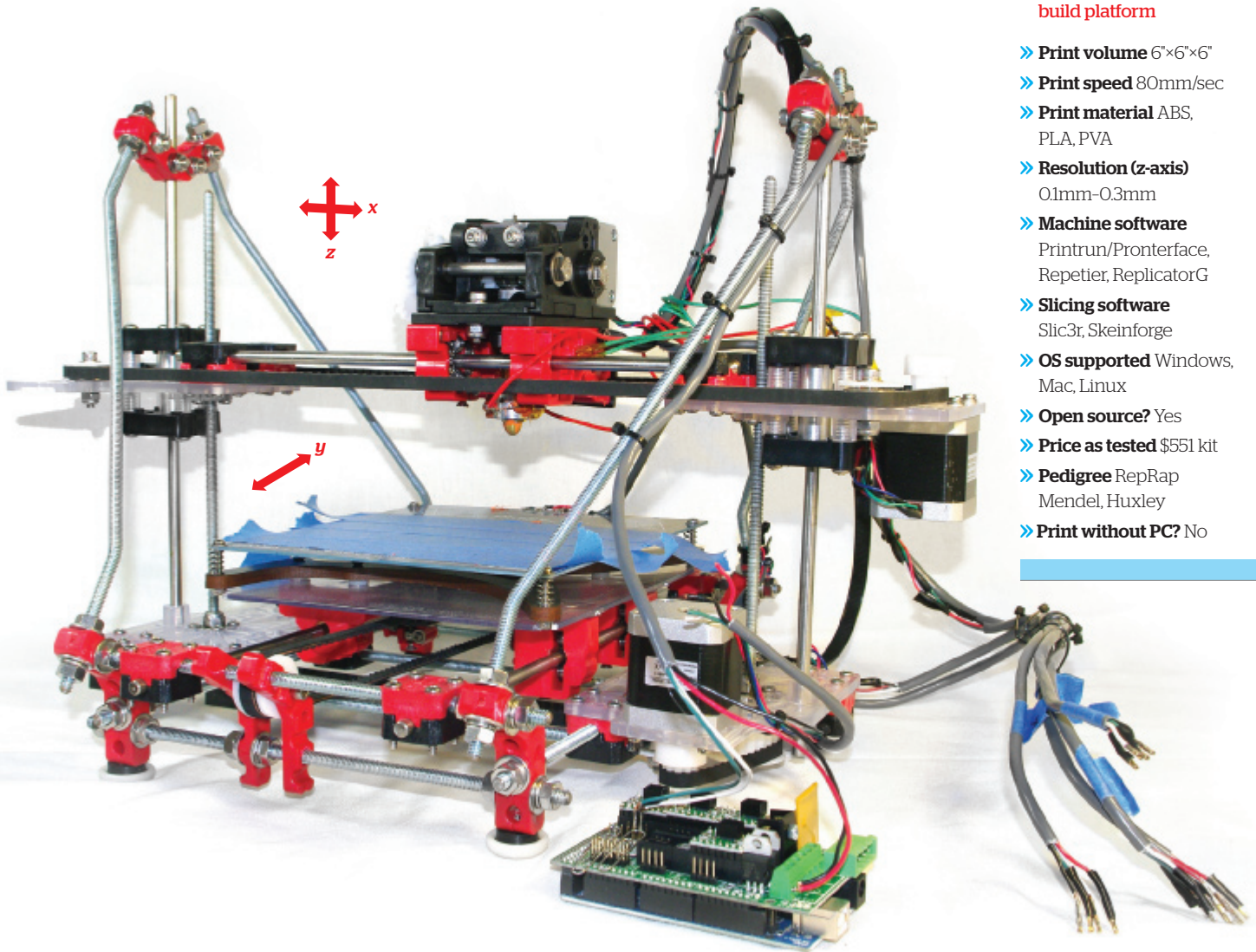
The paper-thin resolution on the High quality setting is amazing, but Medium or Low (Faster) quality settings are great for most jobs.

Active cooling helps sharpen fine details when printing with PLA, but some types of unsupported protrusions may still droop. Try gently tilting the machine just while it's printing chins, noses, or other unsupported features.

THE DETAILS



Leveling the new, bigger build platform is easier with the new three-point system. An injection-molded bracket holds a standard filament spool on the back, clean and simple.



- » **Primo features** Super cheap, injection-molded parts, hot-end takes 1.75mm and 3mm filament, optional heated build platform
- » **Print volume** 6"×6"×6"
- » **Print speed** 80mm/sec
- » **Print material** ABS, PLA, PVA
- » **Resolution (z-axis)** 0.1mm-0.3mm
- » **Machine software** Printron/Pronterface, Repetier, ReplicatorG
- » **Slicing software** Slic3r, Skeinforge
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$551 kit
- » **Pedigree** RepRap Mendel, Huxley
- » **Print without PC?** No

SeeMeCNC H1.1

seemecnc.com

The most do-it-yourself machine we tested – how well it prints is up to you.

TESTED
AND
REVIEWED
BY
**ETHAN
HARTMAN**

WHILE MANY OF THE MACHINES IN THIS ROUNDUP ARE ROOTED IN THE REPRAP MOVEMENT, SeeMeCNC is still very much part of it. Their H1.1 printer kit (\$189-\$594) is a RepRap Huxley with a literal twist: the vertical bars have a slight bend at their ends to alter the geometry; also, SeeMeCNC uses injection-molded connectors rather than

Ethan Hartman

printed ones, a nice upgrade.

While the H1.1 is a nice-looking RepRap, you won't mistake it for a consumer-oriented machine: you're definitely in DIY territory here. First off, there are several electronics options. Among customers who choose RAMPS or RAMBo boards, a popular software solution is pairing Pronterface with Slic3r, though Repetier, ReplicatorG, and Skeinforge are also in the mix.

Interestingly, the H1.1 is also offered with ArtSoft's commercial Mach3 package, but we weren't able to test it with that configuration.

SETUP

Putting the H1.1 together felt like a bit of a throwback. Even though SeeMeCNC was kind enough to send us an assembled machine, I still spent a few hours crimping and soldering to integrate it with a RAMPS board.

The kit instructions look OK for basic assembly, though there seemed to be no obvious place for end-stops.

For that reason, we ran without end-stops and homing, just like in the early days of 3D printing. This necessitated a few tweaks to the startup G-code in Slic3r — basically removing the G28 homing code and replacing it with a G92 to set the current position as home. (In the Printer Settings/Custom G-code tab, my start G-code reads: `G92 X0 Y0 Z0`. In the Printer Settings/General Settings tab, I set the Print Center to `0,0`.)

Spoiler alert: if this sort of thing sounds unpleasant, this is probably not the machine for you. If, on the other hand, this gets your motor running, read on.

After I got the machine up and running with basic functionality, I had trouble locating good instructions for Slic3r configuration, even after diving into the forums. A few quick emails with SeeMeCNC's support got that sorted, however; their help team was very responsive and knowledgeable.

PERFORMANCE

I had a love/hate relationship with SeeMeCNC's "Steve's Extruder": while the design allowed for quickly swapping the hot-end and filament size, it was tricky to keep it aligned while changing

filament, and I had some trouble with plastic sticking to its large nozzle.

And the print results? With a machine this configurable, I'm not sure how meaningful it is to share those. It's the most DIY-feeling unit in this roundup, and it's very much up to you whether that's a good thing — and also up to you how well it prints.

Frankly, I didn't get the results I wanted during my brief time with the SeeMeCNC: for one, I didn't have my temperatures dialed in, leading to some ooze issues. Prints kept popping off the platform because I didn't have the sensor to use with the heated platform. And I was initially printing with PLA, which I don't think showcases this machine at its best. Time ran out before we got it dialed.

For these reasons, we can't really give print quality ratings to the SeeMeCNC. We've seen high-quality prints by other users, so we know they're attainable; it's just a matter of how much effort you're willing to put into it.

But this is a tinkerer's machine, and I'd hardly started tweaking: if you find yourself itching to spend hours perfecting temperature settings, layer heights, and custom start G-code, then the H1.1 might just be the 3D printer for you. And if you're looking for a system to act as a test bed for new extruders or electronics, it's an even more compelling proposition.

If the bleeding edge is more your thing, SeeMeCNC has also been working on another printer: the Rostock Max, a novel delta robot-based design that uses a Bowden-based version of the Steve's Extruder. We'll be quite interested to see how that new machine fares.

CONCLUSIONS

The H1.1 is definitely a throwback: this machine, more than any other in this test, felt like an old-school RepRap, and that made it seem a little out of place.

It's not a 3D printer you'll unwrap and start printing with on Christmas morning; rather, it's a rewarding project for a dedicated tinkerer. And if you're that tinkerer, looking for a RepRap kit to integrate with some parts lying around your tool shed, its \$189 starting price is awfully enticing.

HOW IT COMPARES

Setup	2/5
Documentation	3/5
Ease of Use	2/5
Hardware User Interface	1/5
Machine Software	3/5
Slicing Software	3/5
Speed	4/5
Reliability	2-4/5
Print Quality	2-5/5
Accuracy	2-5/5
Support/Overhangs	2-5/5
Noise	4/5
Value	4/5

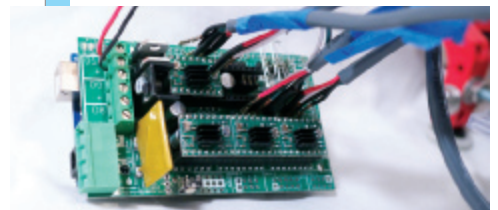
PRO TIPS

If you print with Slic3r and without end-stops, replace the homing code (see my tweaks in "Setup").

SeeMeCNC relies on RepRap documentation; I used reprap.org/wiki/RAMPS_1.4 to wire my electronics.

Help team is responsive, knowledgeable: seemecnc@gmail.com

THE DETAILS



"Steve's Extruder" has dual stainless steel pinch rollers that accept both 1.75mm and 3mm filament. RAMPS electronics are a well-documented standard for RepRap printers — which is good, because you'll solder and crimp the connections yourself.



- » **Primo features** Heated platform, full enclosure, prints out of the box, low price point
- » **Print volume** 6"×6"×6"
- » **Print speed** 50mm/sec
- » **Print material** ABS, PLA
- » **Resolution (z-axis)** 0.1mm-0.3mm
- » **Machine software** Printron/Pronterface
- » **Slicing software** Slic3r
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$699 assembled
- » **Pedigree** Original
- » **Print without PC?** No

Solidoodle 2

solidoodle.com

An undisputed value leader – and a hint of good things to come.

WRITTEN BY
ETHAN HARTMAN

TESTED BY
ETHAN HARTMAN
AND
ERIC CHU

LET'S GET ONE THING STRAIGHT RIGHT OFF THE BAT: the Solidoodle 2 is a machine that simply would not have been possible a few short years ago.

In 2009, when MakerBot introduced the Cupcake CNC kit for under \$1,000, it was a shot across the bow of the professional 3D printer industry: home 3D printing is here. Here's another: the Solidoodle 2 costs \$499 for the base model, prints better than the Cupcake, and comes *completely assembled*.

Solidoodle is the company started by Sam Cervantes, an early MakerBot

alumnus. Like the MakerBots, Solidoodle machines are assembled in Brooklyn, most likely by tattooed, fixie-riding hipsters, and their design leverages the open source RepRap community and DIY printers. Solidoodle has adopted what's become the popular standard: Sanguinololu electronics (reprap.org/wiki/Sanguinololu) and Printron/Pronterface software. There are lively community forums for both projects.

But let's get back to that price point. Yes, \$499, or \$599 with a heated platform, \$699 with a full enclosure. That's "3D printer in every home" money.

How did the scrappy Brooklynites get the price that low? Some corners had to be cut, and for the most part, they were the right ones. The frame is a basic welded box. Rods are secured by hose clamps. A number of brackets and parts are 3D-printed and ugly, though standard practice for RepRaps. (We'd like to see designs for these made available, just in case.) The Solidoodle isn't the prettiest, but none of this should have any functional impact: score one for frugality.

SETUP

While it's doubtful that unboxing will generate the sort of loving pictorials given to new Apple products, the basics are there: assembled printer, USB cable, printed startup guide, one replacement Kapton sheet for the build surface, and a tiny supply of 1.75mm ABS filament. (The Solidoodle will also take PLA, but ABS is recommended.) A bit more filament might be nice; you'd better go buy the color you've been really wanting with some of that money you just saved.

You'll be directed by the startup guide to find setup instructions on the Solidoodle website. These are serviceable, though not best-in-class. If you have trouble, Solidoodle's email tech support was responsive. Don't anticipate being stuck for long.

There are a few pain points, however. You can't load or change filament with the metal enclosure in place, so grab your screwdriver, and be careful — tilt too much as you're removing the top, and you'll tweak the USB connector on the electronics sitting exposed on the back of the machine. (A voltage regulator on our

unit may have been bent during shipping, but didn't have any functional issues.)

You'll want to be mindful whenever you move the Solidoodle. Mr. Cervantes, might we suggest you enclose the electronics on the next generation?

We also discovered that the default baud rate for Pronterface was incorrectly listed, a minor issue that cost us 15 minutes of precious setup time.

PERFORMANCE

So how does it print? Not too bad, though a bit more tuning could go a long way. The single profile included with the Solidoodle resulted in prints that were below average for the printers we tested. Extruder temperature seemed very high, despite nominally being set to a low 190°C. The output was wavy, and overhangs dropped a bit: the owl feathers were among the worst of the bunch.

As the machine lacks an interface, you can only print from a computer. (Tinkerers can no doubt find third-party solutions for this.) Make sure your computer doesn't go to sleep during a long run. Few things are more frustrating than losing a print hours in.

Dialing down the temperature improved things, but we could have spent a lot more time tweaking. On the upside, the machine was fast and reliable; once we figured out that the build plate temperature has to be set manually, we had no trouble. The build plate was well leveled from the factory.

Visiting the websites associated with the printer suggests that the community is hard at work improving the default profiles: blogs like solidoodletips.wordpress.com abound with tweaks, as well as efforts to get good Slic3r profiles.

CONCLUSIONS

Bottom line: It's just about impossible not to like this little bot, and with its low price point, it's an absolute no-brainer for value-minded tinkerers.

For those of us who don't get excited by trading Skeinforge tips, well, it does lag a bit behind its more expensive competition when it comes to out-of-the-box print quality. But with just a few tweaks to the design and software, Solidoodle 2 could easily become the machine to beat.

HOW IT COMPARES

Setup	3/5
Documentation	4/5
Ease of Use	3/5
Hardware User Interface	5/5
Machine Software	3/5
Slicing Software	3/5
Speed	4/5
Reliability	5/5
Print Quality	3/5
Accuracy	2/5
Support/Overhangs	2/5
Noise	4/5
Value	5/5

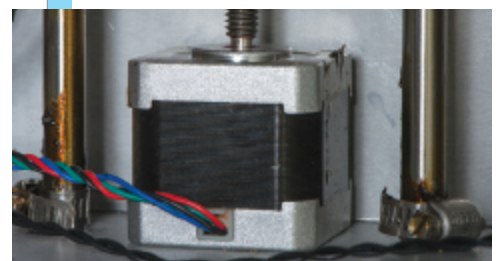
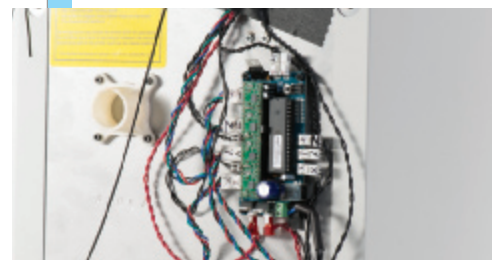
PRO TIPS

Bone up on your favorite slicing program.

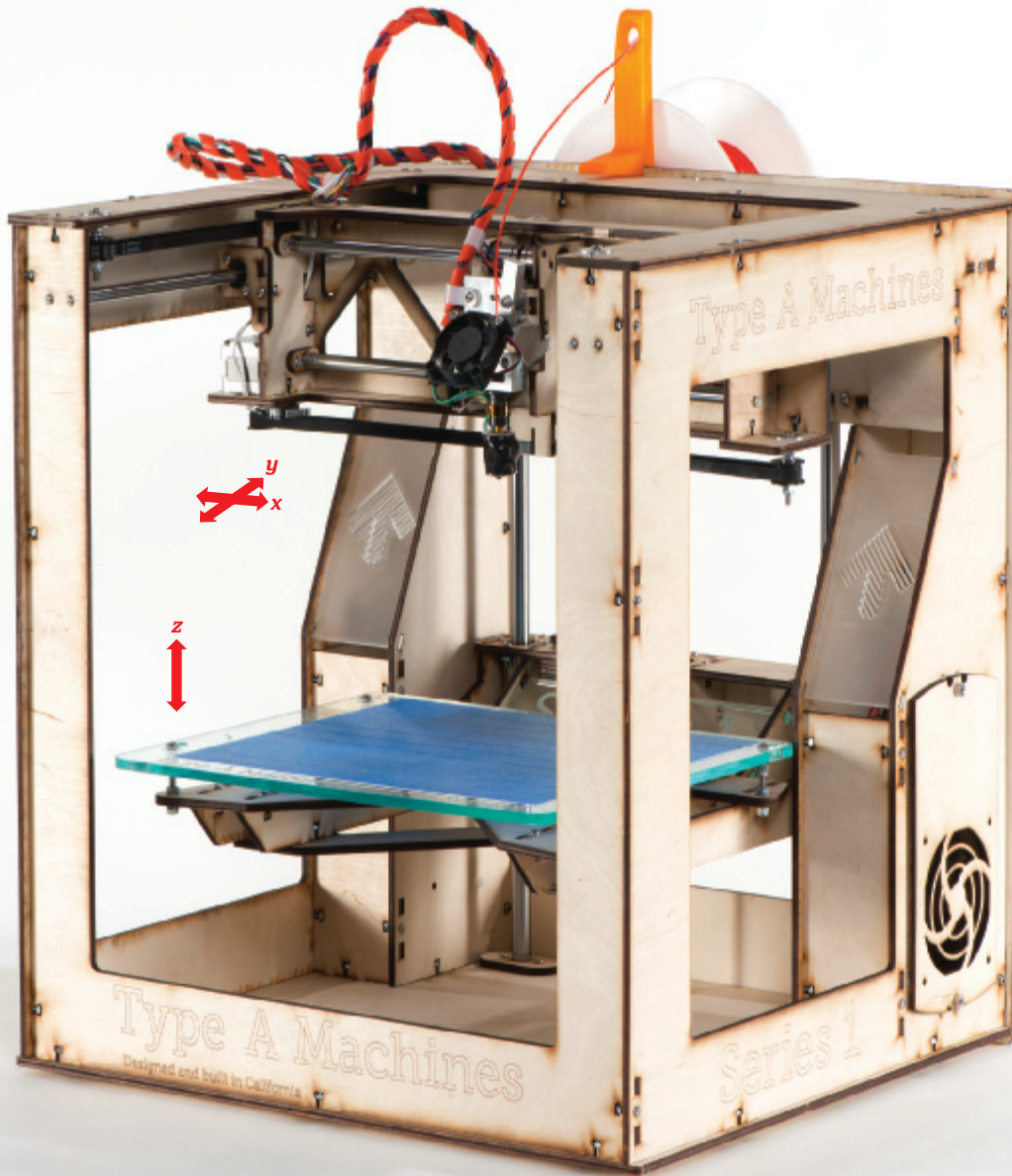
That nozzle seems awfully hot! Tweak if needed.

Make sure your computer doesn't fall asleep and spoil a print job.

THE DETAILS



The scrappy Solidoodle 2 is a clear winner on value, with an optional heated platform and full enclosure to keep ABS prints cozy. And check out those hose clamps! That, my friends, is how to DIY.



» **Primo features** Huge print volume, quick-release build platform, rock-solid extruder

» **Print volume** 9"×9"×9"

» **Print speed** 90mm/sec

» **Print material** PLA, ABS, PVA

» **Resolution (z-axis)** 0.1mm

» **Machine software** Repetier or Printron

» **Slicing software** Slic3r or KISSlicer

» **OS supported** Windows, Mac, Linux

» **Open source?** Yes

» **Price as tested** \$1,400 assembled

» **Pedigree** Original, with RAMPS electronics

» **Print without PC?** No

Type A Series 1

Type A Machines typeamachines.com

An affordable, accurate printer with a huge build area and lots of potential.

WRITTEN BY
ERIC WEINHOFER

TESTED BY
ERIC WEINHOFER AND KEITH OZAR

TYPE A MACHINES' SERIES 1 IS ONE OF THE NEWEST (AND LARGEST) 3D PRINTERS we reviewed, but even though it was released only months ago, it has already made waves in the community due to its huge build area and competitive price.

Based in San Francisco, Type A's tiny crew of Andrew Rutter and a handful of hackers out of Noisebridge and TechShop began constructing Series 1 proto-

types in August 2011. By the time Maker Faire Bay Area rolled around in May 2012, the team had several iterations of their machine on view, and they've been selling the finalized design since mid-year.

Like several printers in our lineup, the Series 1 case is constructed from laser-cut plywood. This route is popular for good reason: plywood is cheap, easy to cut, and paintable.

The Series 1 is an open hardware product, meaning you can download the pertinent case and equipment files from Thingiverse, build your own, and make modifications at will. (We'd like to see someone from this community share a design for a fan shroud to direct air from the diagonally mounted fan toward the nozzle.)

Like MakerBot's Replicator 2, the Type A Series 1 is optimized to print in PLA plastic. PLA is not only a pleasing material to look at, it's also biodegradable (made of cornstarch) and nontoxic. This removes the need (and expense) for a heated print bed for printing ABS plastic, with a minor tradeoff: PLA is more "goopy" than other media under heat. In general, PLA rarely causes warping problems, meaning you can build large objects, and since the included spool of PLA is mounted on a spindle in the back, you don't have to babysit the machine while it's at work.

The machine's 9"-cubed build volume is so big (1.2 liters) that one of the "bonus" prints we did during our review weekend was a full-scale, wearable hat. The jumbo volume is also perfect for printing multiple parts or even whole assemblies at once. The build platform is made of laser-cut acrylic, and it's held in place on the Z stage between the head of a bolt and a spring at each corner. To level it, you simply adjust these 4 bolts; to remove it, just pull it toward you to move larger slots over the 4 bolts, and lift it free.

Type A outfitted our demo unit with their new "Winchester" extruder drive, an element they're still developing for production. Its construction is rock-solid and reliable, with aluminum parts including a lever that keeps your filament tight against the drive gear. A beefy torsion spring keeps the filament in place, and

helps the extruder adjust for minor changes in filament diameter. We're huge fans. Changing plastic is a breeze: simply pull the lever back and slide your filament out. It's also completely exposed, which leads us to believe it'll be easy to troubleshoot and repair. (Type A is also prototyping a Double Winchester for sale in time for the holidays.)

Another benefit of the Series 1's construction: speed. The Type A crew claims their frame design can clock in at printing speeds of 90mm/sec and travel speeds of 250mm/sec. It's also quite accurate — it will print beautifully at a layer thickness of 0.1mm and will happily go all the way down to 0.05mm (50 microns), where the stepping of layers is difficult to detect.

The Series 1 performed extremely well in our test prints. The large bed allowed us to print all parts of the nautilus gears in one go, the owl came out beautifully (even at the tips of the ears), and achieving a perfect snake print was no challenge. However, like many of the other machines, the Series 1 wasn't able to handle the extremely small arch in our "torture test."

Series 1 has a few downsides. Our demo unit was loud, especially when moving at high speeds, a problem that might be minimized with grease and the tightening of bolts. Also, the machine lacked an SD card slot in this configuration. Given that many of today's machines are moving to untethered printing, we'd like to see Type A offer this as standard.

Also disappointing was the lack of documentation on Type A's website. They provide the necessary download links and slicing profiles, but no troubleshooting or instruction on how to use them, as of the time of this review.

CONCLUSION

Overall, we're very happy with this machine. It has a huge build area and it's fast, affordable, and reliable. If you're looking for a PLA-printing machine that works great out of the box at a competitive price, this is your printer. Type A has already proven that they're quick innovators. We look forward to seeing what's next.

HOW IT COMPARES

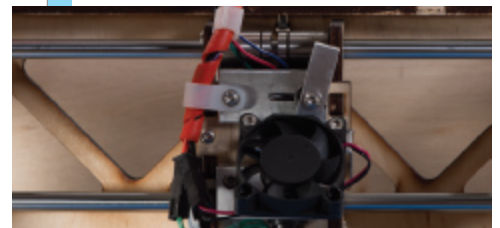
Setup	3/5
Documentation	1/5
Ease of Use	4/5
Hardware User Interface	3/5
Machine Software	3/5
Slicing Software	3/5
Speed	4/5
Reliability	5/5
Print Quality	5/5
Accuracy	4/5
Support/Overhangs	4/5
Noise	2/5
Value	5/5

PRO TIPS

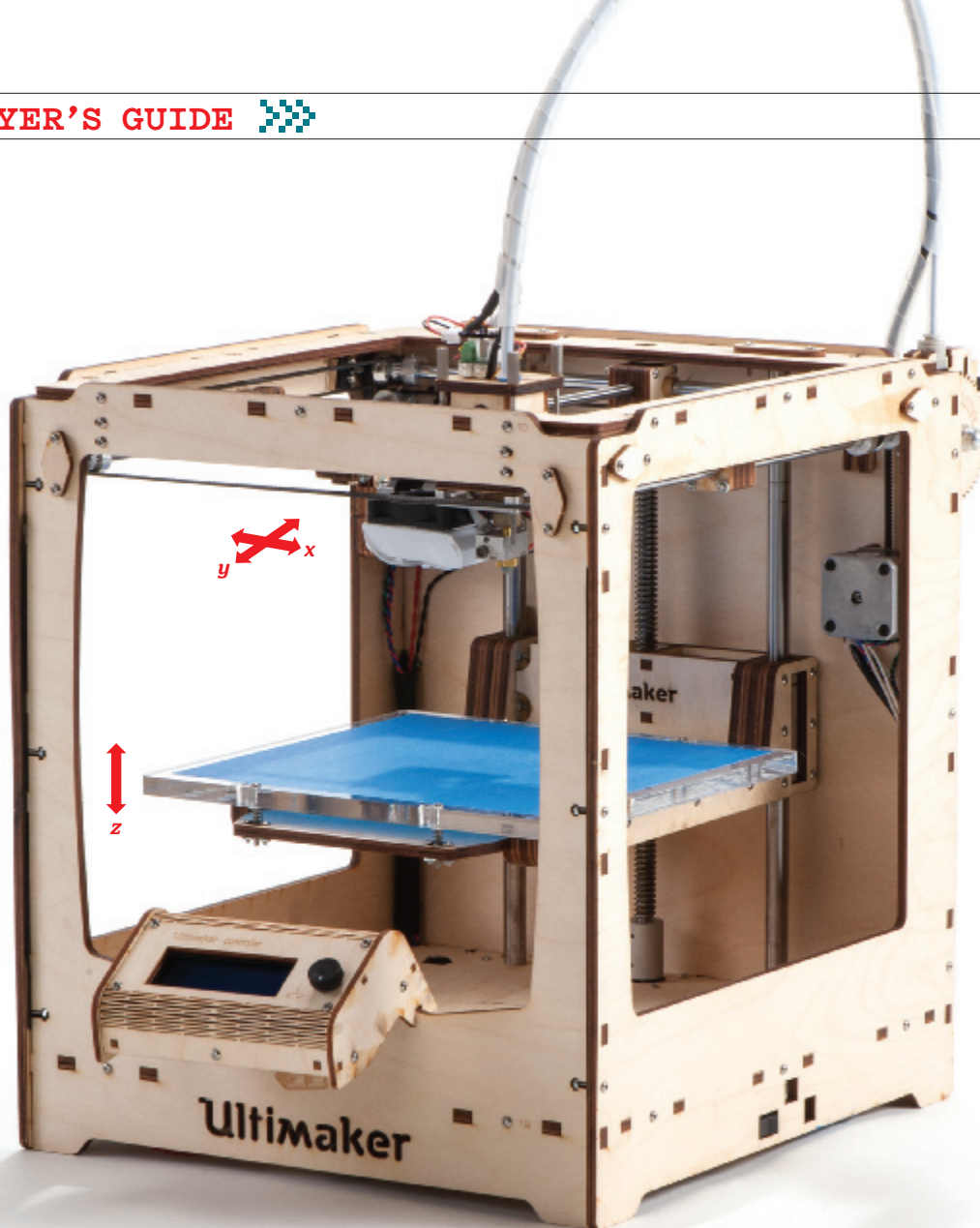
Use a laser cutter to make extra build platforms and minimize time between prints!

For computer-less printing, the Series 1's RAMP electronics support an SD card slot, which is easy for users to install. In fact, Ultimaker's UltiController kit will work with this machine, giving you SD, stand-alone printing, and an LCD-screen interface to boot.

THE DETAILS



We like the rock-solid Winchester extruder with its lever-action filament feeder, and the convenient "Easy-Off" build platform.



- » **Primo features**
High-speed Bowden extruder, huge build volume, fine layer height, optional controller with SD card, active community shares improvements
- » **Print volume** 8.3"×8.3"×8.3"
- » **Print speed** 150mm/sec
- » **Print material** PLA, ABS
- » **Resolution (z-axis)** 0.1mm-0.04mm or finer
- » **Machine software** Cura
- » **Slicing software** Cura
- » **OS supported** Windows, Mac, Linux
- » **Open source?** Yes
- » **Price as tested** \$1,556 kit + \$105 controller
- » **Pedigree** Original
- » **Print without PC?** Optional, SD card

Ultimaker

ultimaker.com

With the fastest, finest prints of any DIY printer, the Ultimaker rewards the patient tinkerer.

TESTED
AND
REVIEWED
BY
**JOHN
ABELLA,
ERIC
CHU,
AND
MATT
GRIFFIN**

NOW 18 MONTHS OLD, THE ULTIMAKER IS A VERITABLE CLASSIC IN 3D-PRINTER-YEARS. But even as it ages, this kit has unique features and a speed-centric design unlike any other printer we tested. Let's see how the machine keeps pace with the new crop of entrants.

Ultimaker was founded in the Netherlands by one of the most active RepRap advocates and developers, Erik de Bruijn, joined by Siert Wijnia and Martijn Elserman. The first Ultimaker kits shipped in early 2011, and the company has grown to more than 20 people.

One of the stated design goals for the Ultimaker is print speed, and the mechanical layout has been optimized for it. The Ultimaker was the only printer

we reviewed to feature a Bowden-style extruder, where the filament drive mechanism is physically separated from the extrusion nozzle. As a result, none of the stepper motors contribute to the weight of the toolhead. This combination of a low-mass toolhead and stationary motors results in an extremely lightweight X-Y gantry system, ideal for fast prints.

Ultimaker also excels in Z resolution. While the printer has a theoretical layer height of 12.5 microns, it's not uncommon for people to print at 40-50 microns with great repeatability.

And the Ultimaker's design hasn't stopped evolving. Updated parts, including new drive bolts and the new V2 hot-end, show a constant drive to improve the product and extend its life. The electronics have been redesigned and updated numerous times. Our review unit also included the UltiController, an add-on that lets you adjust print speed and temperature on-the-fly, print from an SD card, monitor builds, and do other maintenance tasks untethered to a computer.

While the Ultimaker can print in ABS or PLA, it's engineered primarily for PLA, so there's no heated build platform — a near-requirement for large ABS prints.

The Ultimaker remains a great kit for buyers looking to get under the hood. The newest kits ship with the latest parts, and makers can pick and choose as new upgrades become available.

KIT BUILD

The Ultimaker is sold only as a kit; expect assembly to take 6-20 hours, depending on your mechanical ability.

The build was straightforward, thanks to good wiki-based documentation that includes sufficient photos and step-by-step instructions. The number of steps required makes for an intense full-day project or a more leisurely weekend build.

SETUP

Setup was moderately easy. The print bed's leveling process is less fussy than some other printers we tested, and tends to stay level without much intervention. Belts for the x- and y-axis are tensioned with just a hex driver and tend to stay calibrated, but there's no easy way to finely adjust the z-axis limit switch.

For slicing and printing, Ultimaker uses the open source app Cura, which rolls together Skeinforge and Pronterface to create a fast, simple control optimized for the Ultimaker. Cura has a setup wizard that flashes the Marlin firmware onto the Arduino, and a script that tests the limit switches. It also calculates your plastic flow-rate based on your filament dimensions. (Great news: the original developer of Cura now works for Ultimaker.)

Ultimaker offers something else unique from other printers we tested: a commercial version of Netfabb Studio designed to drive their printer. The software costs \$195 and while there was high initial interest, most users seem to be using the open source options instead — and getting similar results.

PERFORMANCE

We achieved excellent quality prints after getting the Ultimaker dialed in — once calibrated, it's the most accurate of the DIY printers. But expect the calibration process to take a while.

How did it do with our "Christmas morning" test prints? We had mixed results. The snake and owl came out great, but the torture test had lots of stringing, mainly due to Cura's default settings not having retraction turned on.

As with many of the hobbyist printers, a lot of printable upgrades exist for the Ultimaker. Replacement and hop-up parts let users modify their system. One such fix is a printable shim to keep the Bowden tube from moving backward during retraction and causing "stringing" on prints; one should probably ship in the box, as we experienced this issue as well. Another option is a battery pack kit that lets you print anytime, anywhere.

CONCLUSIONS

The Ultimaker remains one of the fastest, highest-resolution printers in the hobbyist market. If you want to print exclusively in PLA, it's a competitive choice with a large build area and high extrusion speeds. The company continually upgrades the machine, and users have aced three tough DIY 3D printing benchmarks: fastest, highest resolution, and (at the time) largest prints. These bragging rights bode well for the patient, tinkering-minded maker.

HOW IT COMPARES

Setup	4/5
Documentation	3/5
Ease of Use	4/5
Hardware User Interface	4/5
Machine Software	4/5
Slicing Software	4/5
Speed	5/5
Reliability	4/5
Print Quality	4-5/5
Accuracy	5/5
Support/Overhangs	4/5
Noise	4/5
Value	5/5

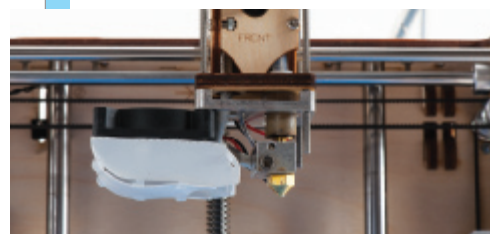
PRO TIPS

Use Cura's setup wizard and any slicer you like. Get expert slicing profiles: makezine.com/3dprinting.

Print this handy clip (thingiverse.com/thing:24363) to stop the Bowden tube moving backward.

Questions? Find answers in Ultimaker's forum and Google group.

THE DETAILS



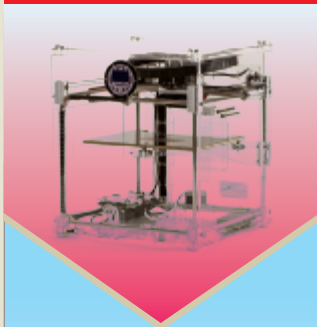
Ultimaker's V2 hot-end is separated from its Bowden extruder, so it's lightweight, fast, and accurate. The UltiController lets you change temperature and speed on the fly, and print untethered with an SD card.

PREMIUM	\$2K+
MIDRANGE	\$1K-\$2K
ENTRY LEVEL	<\$1K

PRICE AS TESTED

Assembled or Kit	
Print Volume	
Print Speed (per Mfr.)	
Print Material	
OS Supported	
Print without computer?	

3D TOUCH

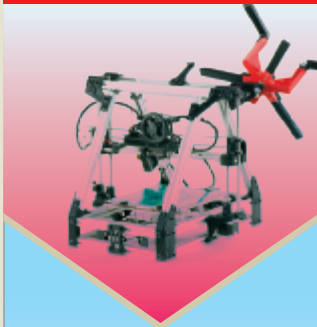


\$4,370

Assembled	
7.3"×10.75"×7.9"	
15mm ³ /sec	
ABS, PLA, Soluble PLA	
Windows	
USB Stick	



LULZBOT AO-100



\$2,500

Assembled	
7.9"×7.5"×3.9"	
150mm/sec	
ABS, PLA	
Windows, Mac, Linux	
SD Card	



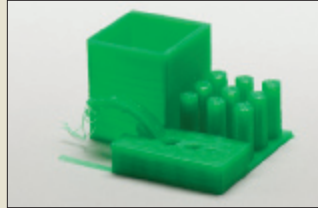
REPLICATOR 2



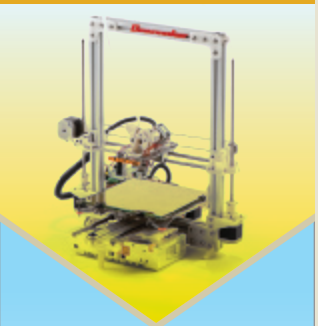
\$2,199

AVAILABLE AT
MAKERSHED.COM

Assembled	
11.2"×6"×6.1"	
80-100mm/sec	
PLA	
Windows, Mac, Linux	
SD Card	



BUKOBOT 8

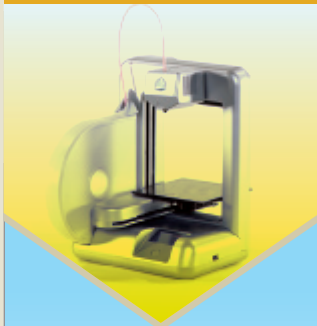


\$1,385

Assembled	
8"×8"×8"	
120mm/sec	
ABS, PLA, PVA	
Windows, Mac, Linux	
Optional, SD Card	



CUBE



\$1,299

Assembled	
5½"×5½"×5½"	
15mm ³ /sec	
ABS	
Windows	
Wi-fi, USB stick	



MENDELMAXPRO

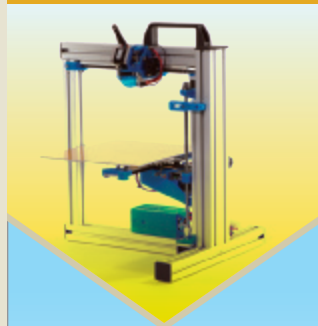


\$1,295

Assembled	
9"×10"×7"	
150mm/sec	
ABS, PLA, PVA	
Windows, Mac, Linux	
Optional, SD Card	

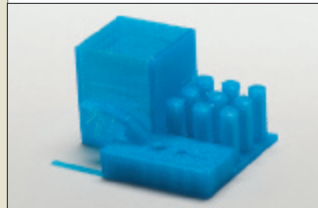


FELIX 1.0

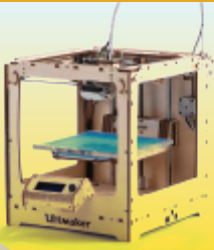


\$1,122

Kit	
10.2"×7.8"×7.8"	
150mm/sec	
PLA	
Windows	
No	



ULTIMAKER



\$1,556

Kit

8.3"×8.3"×8.3"

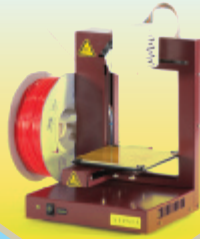
150mm/sec

ABS, PLA

Windows, Mac, Linux

Optional, SD Card

AFINIA H-SERIES



\$1,499

Assembled

5.5"×5.5"×5.3"

3-30mm³/sec

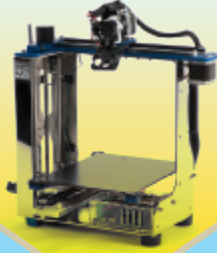
ABS, PLA

Windows, Mac

Onboard File Storage

AVAILABLE AT
MAKERSHED.COM

MAKERGEAR M2



\$1,499

Assembled

8"×10"×8"

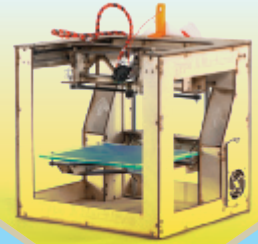
150mm/sec

ABS, PLA

Windows, Mac, Linux

SD Card

TYPE A SERIES 1



\$1,400

Assembled

9"×9"×9"

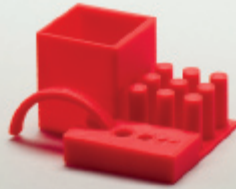
90mm/sec

ABS, PLA, PVA

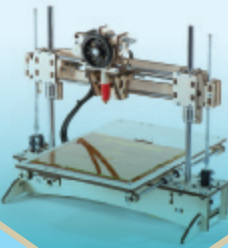
Windows, Mac, Linux

No

AVAILABLE AT
MAKERSHED.COM



PRINTRBOT LC



\$799

Assembled

6"×6"×6"

200mm/sec

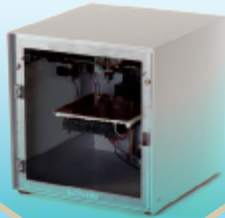
ABS, PLA

Windows, Mac, Linux

SD Card

AVAILABLE AT
MAKERSHED.COM

SOLIDOODLE 2



\$699

Assembled

6"×6"×6"

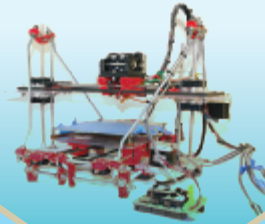
50mm/sec

ABS, PLA

Windows, Mac, Linux

No

SEEMECNC H1.1



\$551

Kit

6"×6"×6"

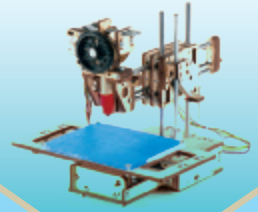
80mm/sec

ABS, PLA

Windows, Mac, Linux

No

PRINTRBOT JR.



\$399

Assembled

4"×4"×4"

100mm/sec

PLA

Windows, Mac, Linux

No

AVAILABLE AT
MAKERSHED.COM



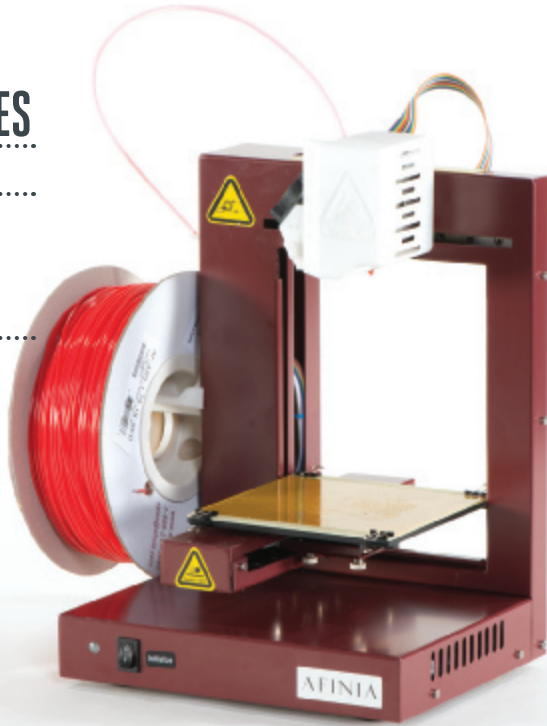
The Standouts

Clear winners in every category.

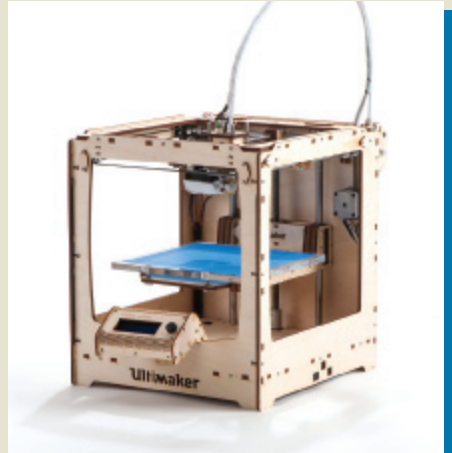
BEST OVERALL EXPERIENCE AFINIA H-SERIES

Review on page 44

Also won for Easiest Setup, and Easiest to Use (tied with Cube)



AVAILABLE AT MAKERSHED.COM



BEST OPEN HARDWARE ULTIMAKER

Review on page 70

Also won for Most Accurate and Fastest

PREMIUM



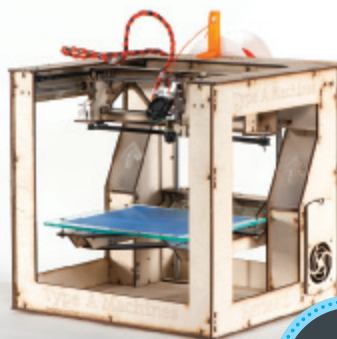
AVAILABLE AT MAKERSHED.COM

BEST IN CLASS REPLICATOR 2

Review on page 62

Runner-up for Most Accurate

MIDRANGE



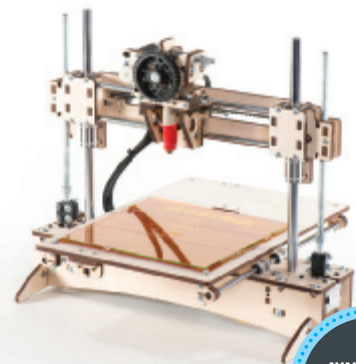
AVAILABLE AT MAKERSHED.COM

BEST IN CLASS TYPE A SERIES 1

Review on page 68

Runner-up for Most Accurate

ENTRY LEVEL



AVAILABLE AT MAKERSHED.COM

BEST IN CLASS PRINTROBOT LC

Review on page 58



Getting Started & User Experience

EASIEST SETUP

AFINIA H-SERIES

Review on page 44

BEST DOCUMENTATION (TIE)

CUBE

Review on page 48

LULZBOT AO-100

Review on page 52

EASIEST TO USE (TIE)

AFINIA H-SERIES

Review on page 44

CUBE

Review on page 48

Performance

FASTEST

ULTIMAKER

Review on page 70

Runner-up: LulzBot

MOST ACCURATE

ULTIMAKER

Review on page 70

Runners-up, 3-way Tie:

Type A Series 1, Bukobot 8, and

Replicator 2

MOST RELIABLE

CUBE

Review on page 48

Notables

MOST INNOVATIVE

BUKOBOT 8

Review on page 46

BEST VALUE

PRINTRBOT JR

Review on page 60

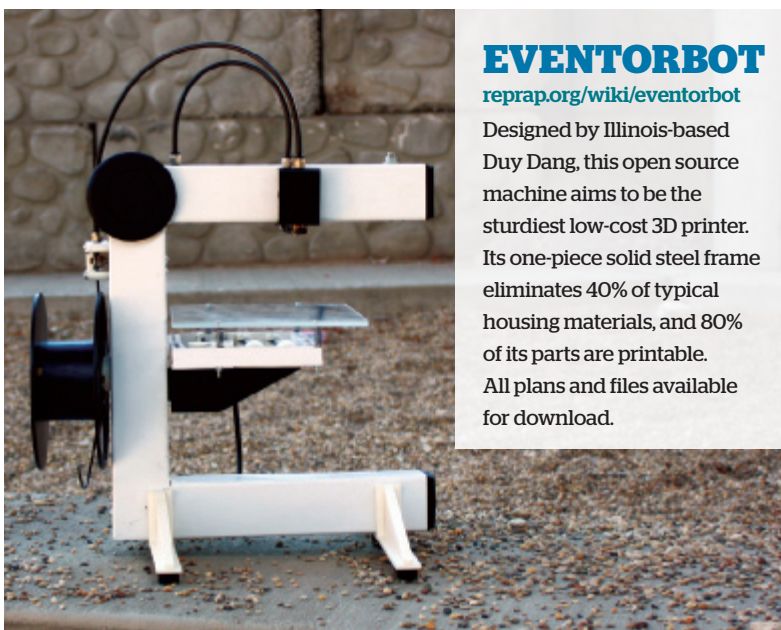
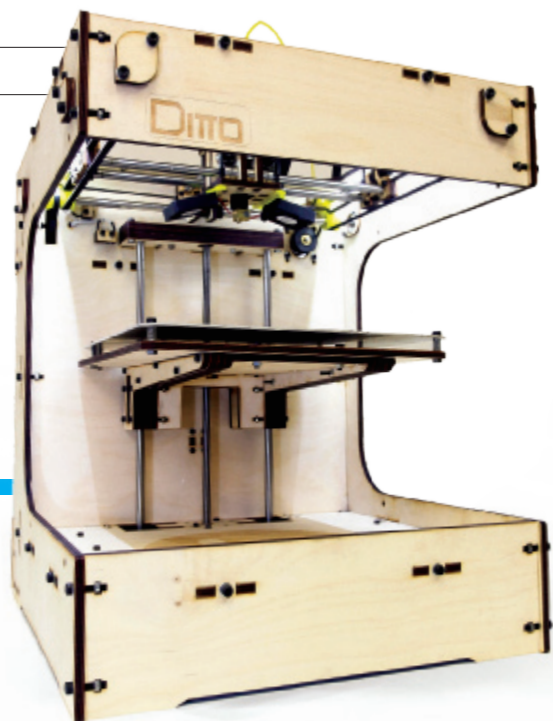
Runner-up: Solidoodle 2

AVAILABLE AT
MAKERSHED.COM

ONES TO WATCH

WRITTEN
BY
GOLI
MOHAMMADI

► **THE 3D PRINTER LANDSCAPE IS A MOVING TARGET**, changing and morphing seemingly every day, largely due to crowdfunding sites like Kickstarter and Indigogo, which enable makers with great ideas to raise funds quickly and go from concept to production in no time. Here's a sampling of up-and-coming 3D printers that caught our eye but weren't available for testing at press time.



EVENTORBOT

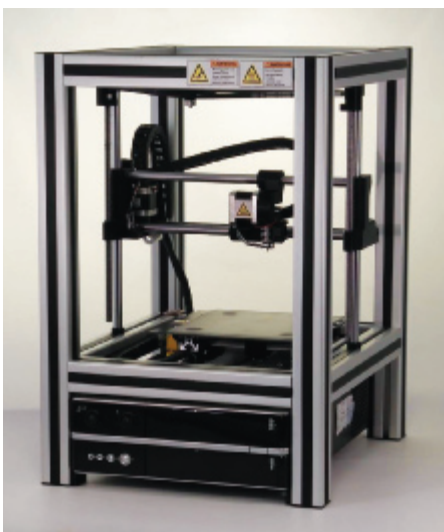
reprap.org/wiki/eventorbot

Designed by Illinois-based Duy Dang, this open source machine aims to be the sturdiest low-cost 3D printer. Its one-piece solid steel frame eliminates 40% of typical housing materials, and 80% of its parts are printable. All plans and files available for download.

THE FABLICATOR

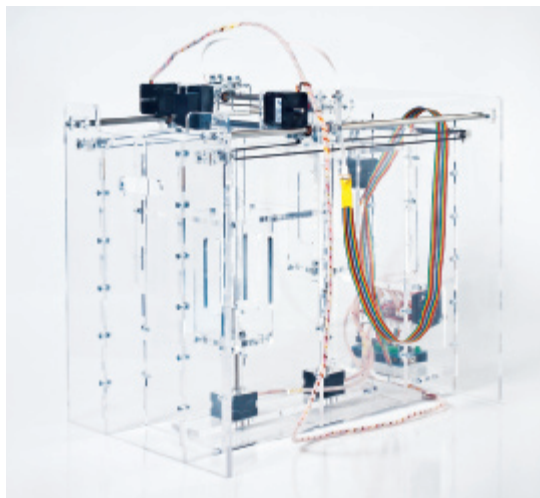
fablicator.com

Penn State graduate Andrew Diehl launched The Fablicator when he wasn't seeing what he wanted in a readily-available printer. The extruded aluminum frame is so sturdy, you can apparently stand on it. It prints in both ABS and PLA, prides itself on print precision, features a borosilicate platform, and includes an integrated Windows 7 computer, but is priced at over \$3000.



DITTO tinkerines.com

Vancouver-based Tinkerine Studio made a splash at this year's Maker Faire New York with their open source Ditto printer. The Ditto boasts user-friendliness for novices and pros alike, a 450-cubic-inch build platform, and an open-front design prime for tinkering with prints, all for \$899 ready to go out of the box.



PWDR pwwr.github.com

The Model O1 is an open source powder-based rapid prototyping machine from the University of Twente in the Netherlands. Made from off-the-shelf parts, it boasts an easy build and can be adapted to perform selective laser sintering (SLS). Usable powder materials include gypsum, ceramics, concrete, and sugar.



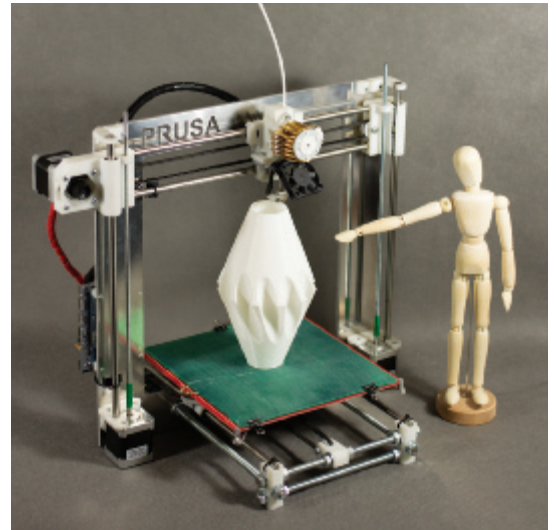
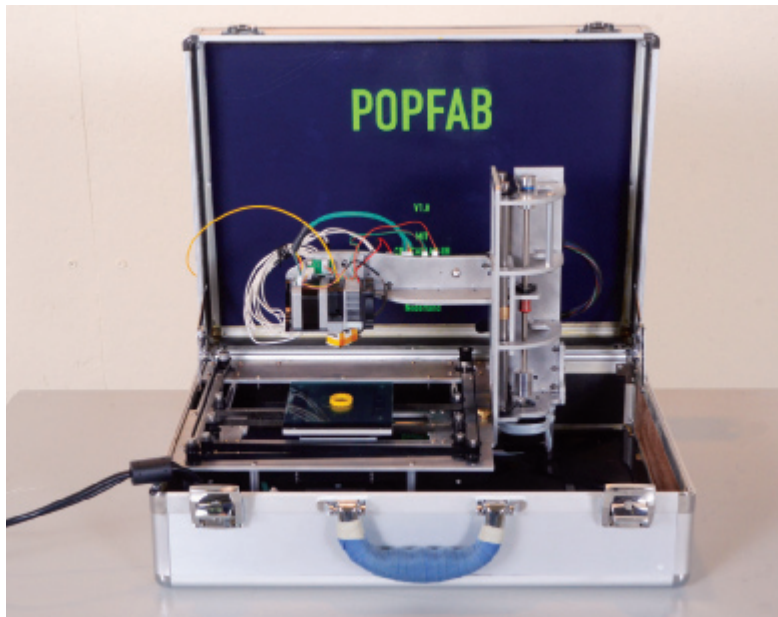
ROSTOCK

reprap.org/wiki/rostock

Designed by Johann C. Rocholl (who was born in Rostock, Germany), the Rostock is a Delta robot-style 3D printer, a parallel-arm mechanism consisting of three arms connected to universal joints at the base, a design popular in pick-and-place machines. SeeMeCNC is looking to have a Rostock Max kit available soon at seemecnc.com.

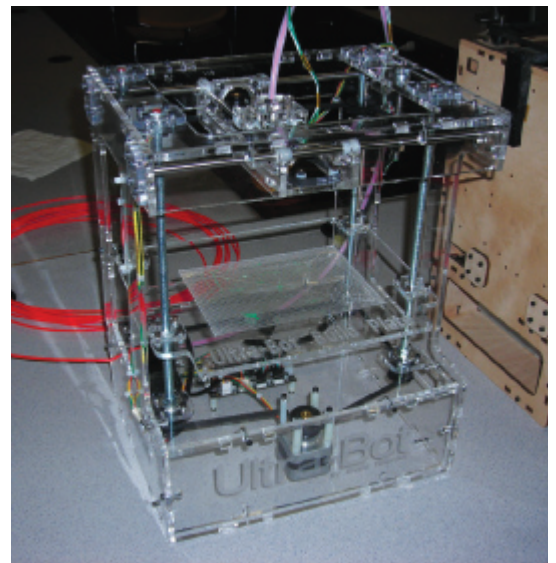
POPFAB vimeo.com/45911972

MIT researchers Ilan Moyer and Nadya Peek have fashioned a workshop in a suitcase-sized metal case with this multi-purpose tool that works as a CNC mill, precision cutter, and 3D printer. The machine has been on international and domestic flights, as carry-on luggage.



PRUSA i3 reprap.org

RepRap core developer and creator of the popular open source Prusa Mendel, Prague-based Josef Průša has a slick new version in the works. The Prusa i3 boasts a build volume 20% larger than the Replicator 2. Plans have not yet been released, and it's unclear whether it'll be available as a kit or strictly DIY, but coming from Průša, it's definitely one to watch. Check out the video footage at youtube.com/user/prusajr.



ULTRA-BOT

makezine.com/go/ultrabot

Indiana-based William Steele designed this clear acrylic machine based on the MakerBot CupCake but with upgrades like a larger build area (6.5"×4.5"×7") and super-quiet micro-step motors. Available as an upgrade (to convert your CupCake), full kit, or assembled.

UP MINI

PP3DP pp3dp.com

TESTED
AND
REVIEWED

BY
GARETH
BRANWYN
AND
ERIC
WEINHOFFER



While we were finishing this issue, a new low-cost version of the Up 3D printer, the Mini, was released by Delta Micro Factory Corp (PP3DP). Since this printer is targeted at a wider consumer market, we thought we'd let MAKE editorial director Gareth Branwyn do a true "Christmas morning" test on it, as he had never set up a 3D printer before. Here's his mini Mini review, with an eventual handoff to a more experienced hand, MAKE product development engineer Eric Weinoffer.

Gareth: The Up Mini offers a great "out of box experience," at least the hardware itself. The fully-enclosed printer (with a 4.7"-cubed build area) is obviously designed to look, feel, and act like any consumer desktop printer: plug, play, print. Like the new Replicator 2, the Mini has a slick black metal and plastic case, but unlike the Rep 2, it's fully enclosed, with a hinged door and a snap-down plastic hood on top. Also like the Rep 2, it has a cold pause feature that allows you to stop mid-print, walk away from the machine, then resume printing when you return.

It's a cinch to set up the Mini, and it comes with all the tools you need: basically a hobby knife, wire cutters, gloves, and a spatula for removing prints from the heated print bed. I had the hardware up and running in minutes.

But then my troubles began. The PDF manual and software are riddled with typos, mangled English, and errors. One of the settings listed in

the manual has two digits reversed. Some of the on-screen error messages are incomprehensible. I spent nearly four hours over two nights trying to generate a print. I ended up with what MAKE contributing editor Brian Jepson dubbed "transporter accidents." I like to think of them as improvisational 3DP art. I posted them on my Facebook page to many "Likes" and giggles.

I think the heart of my problem was that I was in an unheated apartment on a cold and rainy weekend. The print bed never got warm enough for the print to stay put. As soon as a few layers cooled, they'd peel up and the piece would start moving around, destroying the print. An enclosure like the one on the Mini is supposed to address these temperature and draft problems, but it wasn't enough in my case.

Frustrated, I passed the printer on to our product development engineer, Eric Weinoffer. He had better success.

For \$899 the Up Mini is impressive, and if you're willing to futz you'll likely find it a solid beginner machine. A true consumer 3D desktop printer with an uneventful out-of-box experience, it nevertheless still has a ways to go. With better software, a readable manual, and a more reliable print bed, the Mini could prove a real contender.



*Gareth's first print of the snake (above).
Eric's final print of the snake (below).*



Eric: I didn't bother with the manual! Thankfully, I'd already had two days to play with the Up Mini's bigger brother, the Up/Afinia H-Series (see page 44), during our 3D Print Shop Weekend. In fact, after a few hours of use, I'd say the Up Mini is just a lower-cost Up/Afinia with a slightly smaller build volume and a fancy black enclosure. The Afinia is a fantastic machine, and the Mini appears to offer most of what the Afinia does for some \$600 less: good-quality prints with semi-untethered printing (you can unplug your computer once the print begins).

Unfortunately, the Afinia and Up Mini also share some shortcomings. Like Gareth, I experienced software crashes. The software is also closed source and somewhat clunky to navigate. And I would surely rip out the loud, annoying piezo buzzer within an hour of unboxing it.

I also ended up having some print bed leveling issues. Still, a mini Up for \$899? Not bad.

STEP INTO LIQUID

► **RESIN-BASED PRINTERS ARE THE HOT NEW TECH IN 3D PRINTING.** In a nutshell, instead of melted plastic printed from the end of an extruder, these machines cure liquid resin layer-by-layer using light, yielding the highest-resolution prints.



FORMLABS FORM 1 formlabs.com

David Cranor, Maxim Lobovsky, and Natan Linder of the MIT Media Lab created the Form 1 and raised more than \$2 million on Kickstarter for the project. Their stereolithography system directs a laser across a tray of liquid photopolymer resin to solidify one layer at a time, with the build platform raising the object after each layer. Pro-grade prints with 300-micron features and 25-micron Z resolution are possible. The team previewed the Form 1 at World Maker Faire New York to raves.



B9CREATOR

b9creator.com

South Dakota-based Michael Joyce raised more than a half-million dollars – 10 times his intended funding goal – on Kickstarter for this open source, resin-based 3D printing system that boasts superior print resolution. A digital light processing (DLP) projector shines an image onto a layer of photo-initiated polymer resin, resulting in a quick, solid cure of the entire layer in one operation, at a minimum 100-micron resolution. Prints as fine as 50 microns X-Y resolution and less than 10 microns Z resolution are possible.



▶ All kinds of makers, artists, designers, and startups are taking advantage of the boom in 3D printing services to sell an amazing variety of custom-made or customizable objects. Here's a sampling of what's out there.

Rubber Sole

Continuum Fashion's Strvct nylon shoes are strong, lightweight, and made to order. After printing, they're fitted with a patent leather inner sole and coated with rubber on the bottom for traction. The designers also made headlines with their 3D-printed bikini (see page 19).

\$900 continuumfashion.com



WRITTEN
BY
ERIC
CHU

3D Products Now ON THE MARKET



8-Bit Eyewear

San Francisco-based Protos Eyewear sunglasses are stylishly oversized, and the company promises custom fitting soon. Their Hal Pixel model stands out with its Lego/8-bit look.

\$250 protoseyewear.com

Cinemo (Sculpteo); Polychemy



Teeth Time

Teeth Tea Cup by artist Lily X. Su is printed by Shapeways in a glazed ceramic material that feels exactly like traditional ceramic-ware and is food-safe as well. Known for their 3D-print-and-ship service, Shapeways also has an online marketplace where makers sell prints of their designs; some can be printed in glass, stainless steel, and sterling silver.

\$111 shapeways.com/model/622409

Make Your Case

Customize Sculpteo's iPhone cases using a web or iPhone app: choose a base model and color, and add your own text, designs, photos, design parameters like custom curves, or even 3D terrain from Google Earth. Sculpteo also offers a marketplace for 3D artists to sell their works.

\$25-\$40 3dpcase.sculpteo.com

Polychemy's iPhone cases are printed in a strong, flexible nylon plastic called polyamide, and you can have your name custom-printed into the case. The Singapore-based design boutique also sells 3D-printed jewelry and sculpture.

\$42 polychemy.com



Vintage Verve

MakerBot Mixtape is a twist on the old-school cassette mixtape and the modern MP3 player. The 3D-printed case holds an MP3 player circuit that stores 2GB of music; load it with tunes for someone special. The electronics are also available as a kit for those who want to print their own case.

\$39 store.makerbot.com





DESERT MANUFACTURER

Markus Kayser's sand and sun 3D printer.

▶ THINK THAT DESERTS LACK RESOURCES?

Not to Markus Kayser. The MIT research assistant with a master's in product design has created a 3D printer that can make glass objects using a desert's two most abundant resources: sun and sand. "I began asking myself," says Kayser, "what if I could build a machine which would act as a kind of translator between the two?" His Solar Sinter is the direct result.

Based on a type of 3D printing known as selective laser sintering (SLS), Kayser's Solar Sinter uses the sun's rays as a laser and sand rather than resins to create exact physical

replicas of his digital designs. The printer includes a large Fresnel lens that's always facing the sun by way of an electronic sun-tracking device, stepper motors to move and load its sandbox, and two 60-watt photovoltaic panels that provide electricity to charge the battery that drives the motors and electronics of the machine.

His first time out with Solar Sinter, Kayser produced both a bowl and a tile, as well as a sculptural piece. "Once I input the design I'm trying to produce via an SD card," he says, "the machine reads its code and then moves the sandbox along to the correct

x and y coordinates at 1mm per second, while the lens focuses a light beam that produces temperatures between 1,400°C and 1,600°C, more than enough to melt the sand." The objects are built layer by layer over the course of several hours.

"[In the future] printing directly onto the desert floor with multiple lenses melting sand into walls and eventually building architecture in desert environments could be a real prospect," Kayser muses.

markuskayser.com/work/solarsinter

Laura Kiniry is a San Francisco-based freelance writer and regular MAKE contributor.

WRITTEN
BY
LAURA
KINIRY



Markus Kayser



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DREAM MACHINE

Dissolving the boundaries between imagination and physical reality.

▶ **AS AN ARTIST, I'VE ALWAYS BEEN DRIVEN TO CREATE ART THAT NO ONE HAS EVER SEEN BEFORE.** My search for the innovative led me to computers in the early 80s. I recognized the potential for digital technology in art and immersed myself.

A career in visual effects put me at the cutting edge of this technology, where I could explore and experiment with digital 3D tools, like procedural modeling and volumetric sculpting, and apply them in unintended ways. I learned to build brand new tools and processes that made no attempt to emulate traditional

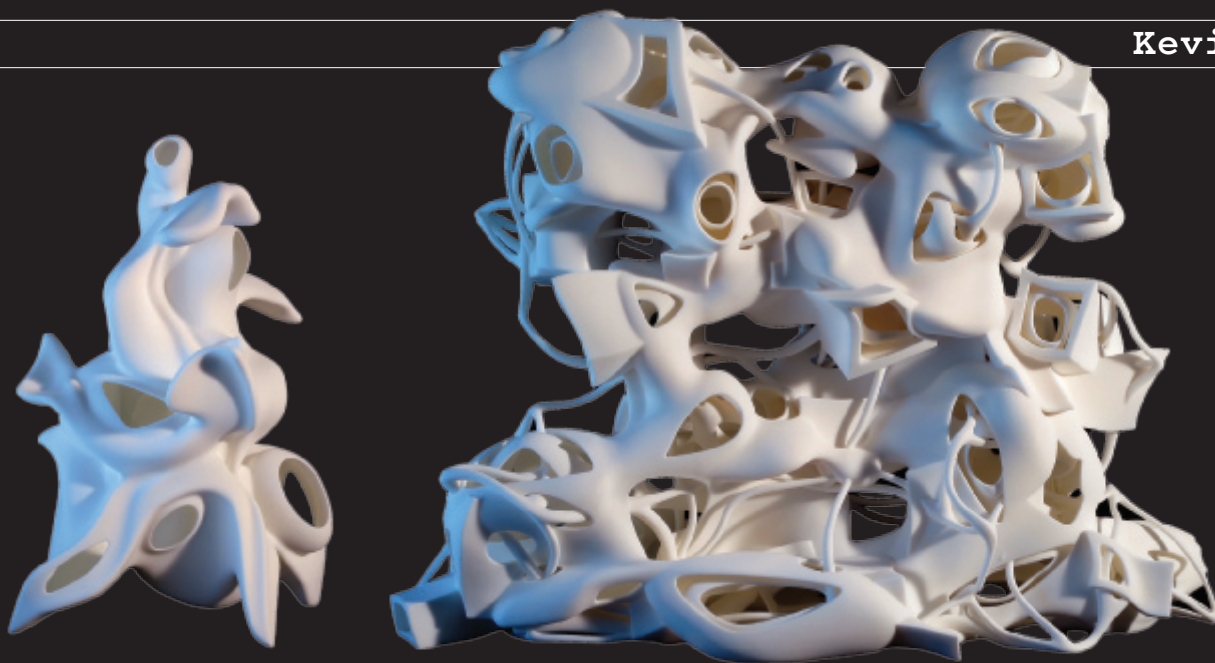
WRITTEN &
PHOTOGRAPHED BY
KEVIN MACK

methods. These processes resulted in unique virtual artifacts that imbued my digital objects with a surreal and mysterious quality. They were new.

As these newfound capabilities enabled my wildest art ambitions, along came 3D printing, which made it possible to manifest my digital creations in the physical world. It was like a science fiction dream come true.

One reason I find 3D printing so compelling is that it enables production of objects that could not be made in any other way. Rapid prototyping lacks many of the





When you experience these objects and hold them in your hands, there is an immediate intuitive awareness that you are seeing something that wasn't possible before. This can be a profoundly surreal experience.



limitations of traditional object-creation methods. By exploiting these capabilities, I'm able to add a powerful dimension to my sculptures: not only are they new, but they appear to be impossible.

Humans are immersed in the world of manufactured objects, and our brains have an intuitive understanding of how things are made. We've come to expect certain artifacts of the fabrication processes, such as seams, limited part complexity, and lack of compound curvature. 3D printing enables the creation of objects that conspicuously defy these expectations. When you experience these objects and hold them in your hands, there is an immediate intuitive awareness that you are seeing something that wasn't possible before. This can be a profoundly surreal experience.

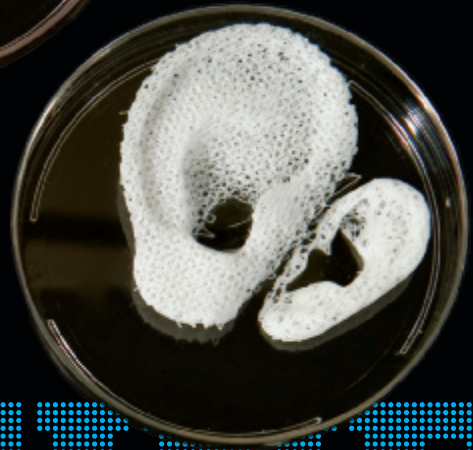
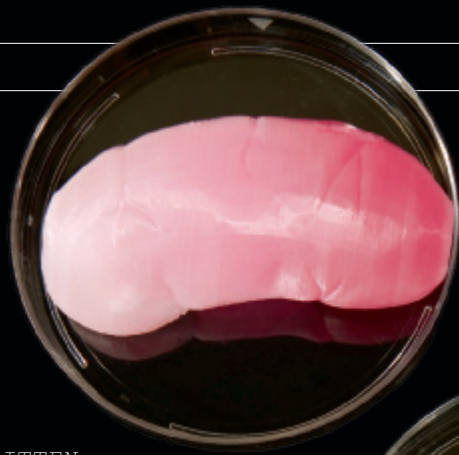
My dream of creating art that no one has ever seen before has come true. Digital technology and 3D printing open up a vast space of entirely new aesthetic possibilities. I am creating and discovering unimaginable forms and sculptures that couldn't exist before.

This is just the beginning. Technology is

constantly advancing. In the future, I predict that creative technologies will completely dissolve the boundaries between imagination and physical reality. I don't know if the world is ready, but I can't wait.

Kevin Mack is a pioneering digital artist and Academy Award-winning visual effects designer. Mack uses science and technology to make art that depicts and inspires the transcendent. kevinmackart.com





3D

WRITTEN
BY
GOLI
MOHAMMADI
AND
CRAIG
COUDEN

PRINTING IN

MEDICINE

From tissue to organs to bones and beaks, the future of medicine is 3D printed.



REVOLUTIONARY REPLACEMENTS

Researchers at Wake Forest University's Institute for Regenerative Medicine in North Carolina have created a one-of-a-kind 3D printer designed to print replacement tissues and organs. Data from CT or MRI scans is used to first create a 3D model. Living cells and biomaterials that hold the cells together are then printed into 3D shapes and implanted in the body, where they continue to develop. The structures are not functional until implanted, using the body's natural regenerative processes to complete the implant. The team has successfully engineered a miniature kidney capable of producing urine-like fluid when implanted in a steer and aims to 3D print similar versions for humans. makezine.com/go/wakeforest



BEAUTY AND THE BEAK

After a poacher in Alaska shot off her upper beak, Beauty the Bald Eagle was found emaciated, unable to eat, drink, or preen her feathers, her tongue and sinuses exposed. Despite recommendations she be euthanized, raptor specialist Jane Cantwell of Birds of Prey Northwest took her in and began looking for solutions.

During a presentation in Idaho, Cantwell met Nate Calvin, founder of Kinetic Engineering Group, who was moved to help. Despite having no previous experience with prosthetics, Calvin spent 200 hours designing a replacement beak by making a mold of the remaining beak, scanning it, modeling in SolidWorks, and having a temporary beak 3D printed in a nylon composite. A titanium baseplate was affixed to Beauty's remaining upper beak to act as a guide, and the new beak attached. The final beak was 3D printed in titanium.

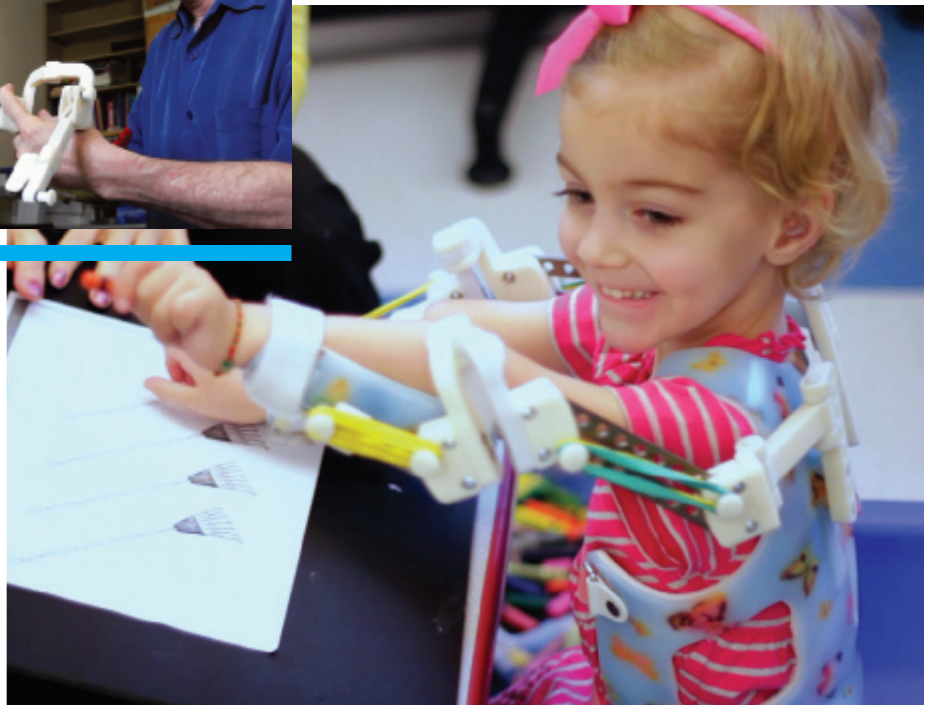
makezine.com/go/beauty

MAGIC ARMS



Using hinged metal bars and resistive rubber bands, the Wilmington Robotic Exoskeleton (WREX) gives patients with underdeveloped arms a wide range of arm motion. The original WREX, made from machined parts, fit children as young as 6, but for 2-year-old Emma Lavelle, researchers discovered they could 3D print smaller, lighter parts. Printed using a Stratasys Dimension 3D printer, the ABS plastic exoskeleton allows for easy customization and fine-tuning for the 15 children now using it.

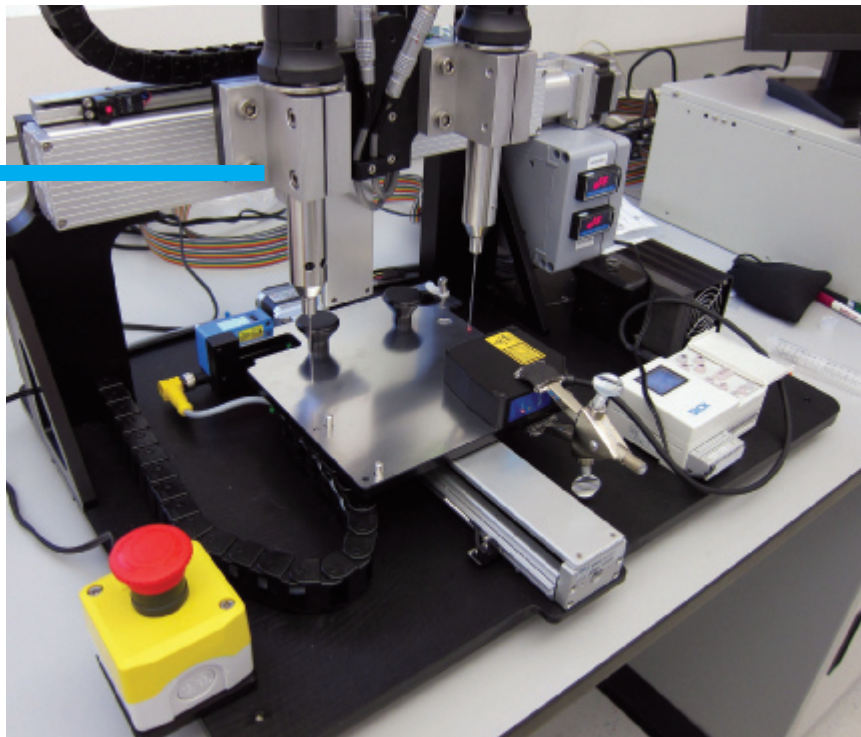
makezine.com/go/stratasys





TISSUE ENGINEERING

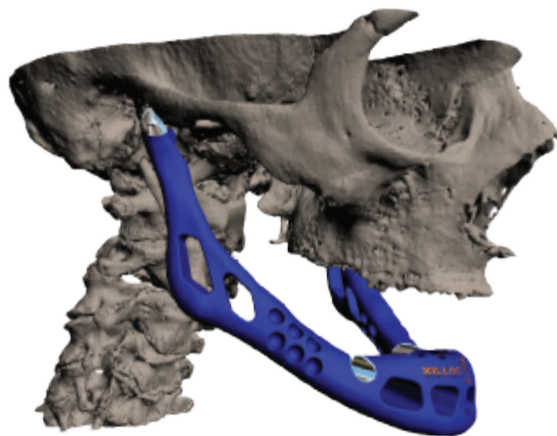
San Diego-based innovators Organovo have engineered several custom, commercial NovoGen MMX Bioprinters, capable of printing tissue structures. The machines feature dual extruders: one that prints a water-soluble gel that acts as the scaffolding, and another that fills the armature with a bio-ink of living cells (each drop containing 10K to 30K cells) that naturally flow together and fuse. The fundamental nature of biological materials is to self-organize, and after an incubation period, the cells continue to develop and grow without the gel component. The team has been able to print a 1mm-diameter, 5cm-long blood vessel in 30 minutes. organovo.com



Bespoke Innovations; Organovo

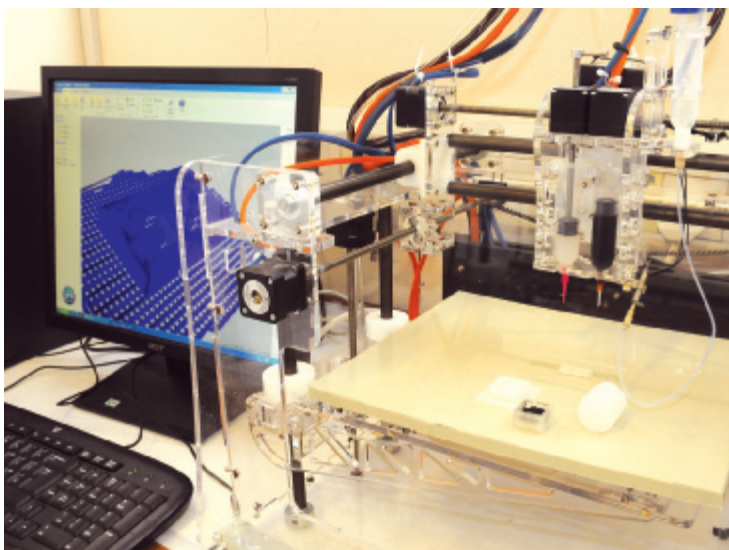
DESIGNER PROSTHETICS

Bucking the typical one-style-suits-all model of conventional prosthetics, San Francisco-based Bespoke Innovations makes custom coverings, called Fairings, that surround an existing prosthetic leg, recreating the user's natural leg shape through 3D scanning, designing, and printing. Conceived by industrial designer Scott Summit and orthopedic surgeon Dr. Kenneth Trauner, Bespoke Fairings are designed in collaboration with the patient, aiming to reflect the individual by offering a number of material and pattern options, including leather, chrome plating, and tattoos. bespokeinnovations.com



JAWS OF INNOVATION

A Dutch woman in her 80s was fitted with a 3D-printed jawbone after having her infected mandible removed. Belgian company LayerWise modeled the replacement from a CT scan of the original bone. Using selective laser sintering, the replacement was made of titanium and covered with a bioceramic coating. The replacement weighed just over an ounce more than the original, and the woman was reportedly speaking within hours after surgery. makezine.com/go/jaw



NOT YOUR AVERAGE CHEM SET

Researchers at the University of Glasgow have developed a way to synthesize custom labware on a much smaller scale. Using a low-cost 3D printer and open source CAD software, researchers printed customized vessels, called "reactionware," out of polymer gel laced with chemical reagents that foster chemical reactions (think of an Erlenmeyer flask infused with chemicals for that day's lab experiment). It could eventually lead to pharmacists making small, customized batches of medicines for individual patients. makezine.com/go/reactionware

PRINT CRIME

A futuristic excerpt from *Overclocked: Stories of the Future Present*.

THE COPPERS SMASHED MY FATHER'S PRINTER WHEN I WAS 8. I remember the hot, cling-film-in-a-microwave smell of it, and Da's look of ferocious concentration as he filled it with fresh goop, and the warm, fresh-baked feel of the objects that came out of it.

The coppers came through the door with truncheons swinging, one of them reciting the terms of the warrant through a bullhorn. One of Da's customers had shopped him. The ipolice paid in high-grade pharmaceuticals — performance enhancers, memory supplements, metabolic boosters. The kind of things that cost a fortune over the counter, the kind of things you could print at home, if you didn't mind the risk of having your kitchen filled with a sudden crush of big, beefy bodies, hard truncheons whistling through the air, smashing anyone and anything that got in the way.

They destroyed grandma's trunk, the one she'd brought from the old country. They smashed our little refrigerator and the purifier unit over the window. My tweetybird escaped death by hiding in a corner of his cage as a big, booted foot crushed most of it into a sad tangle of printer wire.

Da. What they did to him. When he was done, he looked like he'd been brawling with an entire rugby side. They brought him out the door and let the newsies get a good look at him as they tossed him in the car. All the while a spokesman told the world that my Da's organized-crime bootlegging operation had been responsible for at least 20 million in contraband, and that my Da, the desperate villain, had resisted arrest.

I saw it all from my phone, in the remains of the sitting room, watching it on the screen and wondering how, just how anyone could look at our little flat and our terrible, manky estate and mistake it for the home of an

WRITTEN
BY
CORY
DOCTOROW

organized crime kingpin. They took the printer away, of course, and displayed it like a trophy for the newsies. Its little shrine in the kitchenette seemed horribly empty. When I roused myself and picked up the flat and rescued my poor peeping tweetybird, I put a blender there. It was made out of printed parts, so it would only last a month before I'd need to print new bearings and other moving parts. Back then, I could take apart and reassemble anything that could be printed.

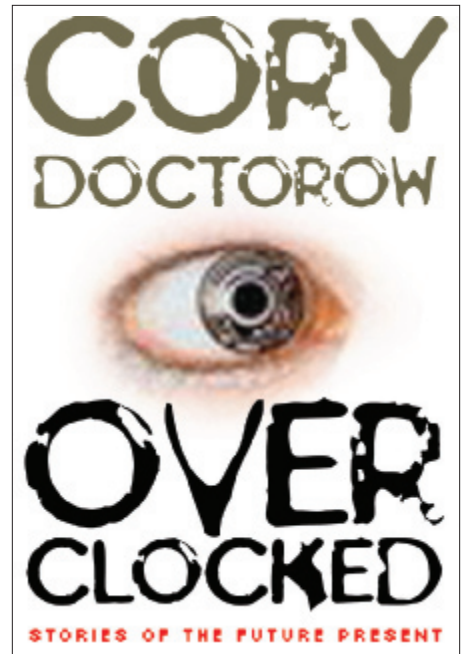
“You're a smart girl, I know that. You wouldn't know where your old Da could get a printer and some goop?”

By the time I turned 18, they were ready to let Da out of prison. I'd visited him three times — on my tenth birthday, on his fiftieth, and when Ma died. It had been two years since I'd last seen him and he was in bad shape. A prison fight had left him with a limp, and he looked over his shoulder so often it was like he had a tic. I was embarrassed when the minicab dropped us off in front of the estate, and tried to keep my distance from this ruined, limping skeleton as we went inside and up the stairs.

“Lanie,” he said, as he sat me down. “You're a smart girl, I know that. You wouldn't know where your old Da could get a printer and some goop?”

I squeezed my hands into fists so tight my fingernails cut into my palms. I closed my eyes. “You've been in prison for 10 years, Da. Ten. Years. You're going to risk another 10 years to print out more blenders and pharma, more laptops and designer hats?”

He grinned. “I'm not stupid, Lanie. I've learned my lesson. There's no hat or laptop that's worth going to jail for. I'm not going to



print none of that rubbish, never again.” He had a cup of tea, and he drank it now like it was whisky, a sip and then a long, satisfied exhalation. He closed his eyes and leaned back in his chair.

“Come here, Lanie, let me whisper in your ear. Let me tell you the thing that I decided while I spent 10 years in lockup. Come here and listen to your stupid Da.”

I felt a guilty pang about ticking him off. He was off his rocker, that much was clear. God knew what he went through in prison. “What, Da?” I said, leaning in close.

“Lanie, I'm going to print more printers. Lots more printers. One for everyone. That's worth going to jail for. That's worth anything.”

Copy this story: craphound.com/?p=573

Cory Doctorow (craphound.com) is a science fiction author, activist, journalist and blogger, co-editor of *Boing Boing* (boingboing.net), and the author of the bestselling Tor Teen/HarperCollins UK novel *Little Brother*. His latest novel is *For the Win*, a young adult novel; his latest short story collection is *With a Little Help*.

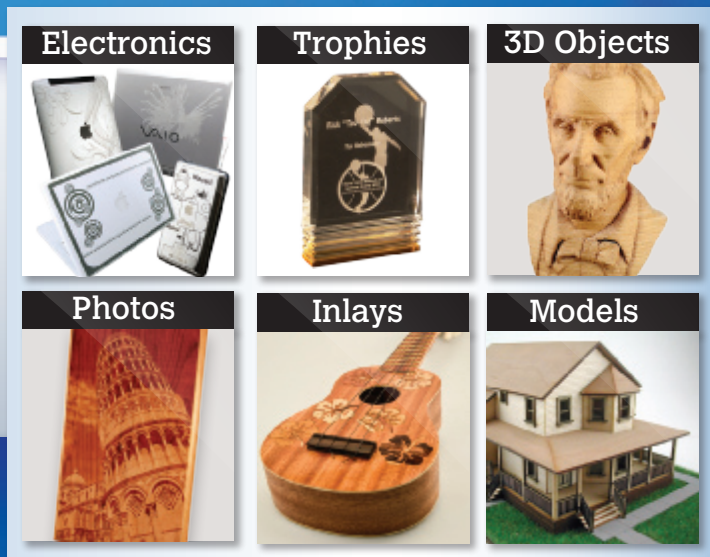
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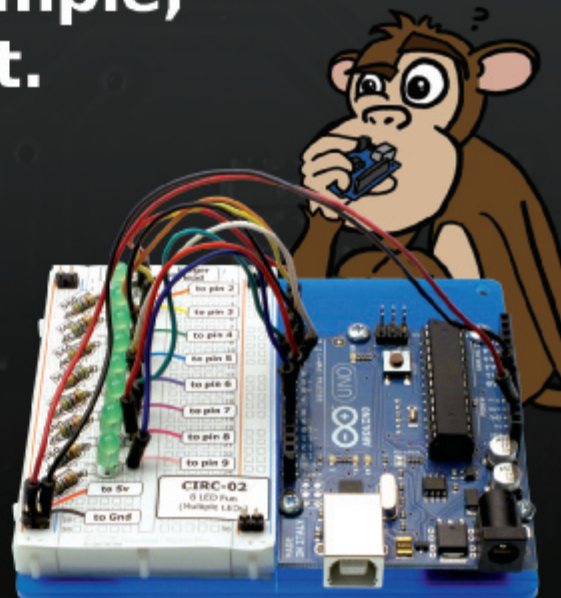
Arduino made so simple, monkeys could do it.

They actually tried to eat it,
but it's still pretty darn simple.

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TIME REQUIRED: A Few Hours
DIFFICULTY: Moderate

SKILL BUILDER:

3D SCANNING

Use Kinect, ReconstructMe, and 123D Catch to capture 3D models of stuff in the real world – then clean them up for 3D printing.

WRITTEN
 BY
 ANNA
 KAZIUNAS
 FRANCE

► **Welcome to the bleeding edge.** You no longer need an expensive high-end 3D scanner to create good-quality scans that are suitable for 3D printing. There are now an increasing number of affordable ways to digitize physical objects. Some of them require additional hardware with a RGB camera and depth sensors, like a Microsoft Kinect or an Asus Xtion, but you can also use your phone or a digital camera to capture images. These images can then be converted into 3D models, cleaned up using mesh repairing software, and then printed on your MakerBot or other 3D printer.

WHAT IS 3D SCANNING?

A 3D scanner collects data from the surface of an object and creates a 3D representation of it. The Kinect and Xtion both work by beaming infrared light at an object, and measuring how far away each reflected point of light is. It then turns each individual point

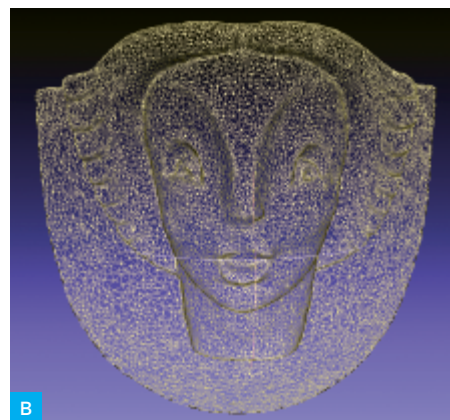
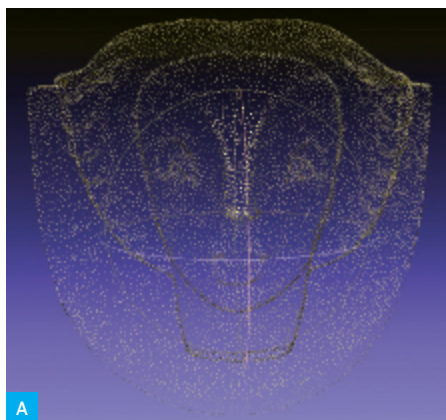
into a collection of points called a *point cloud* (Figure A). Each point in the cloud is represented with an X, Y, and Z coordinate.

This point cloud is processed (or *reconstructed*) using scanning software into a digitized representation of the object, known as a *mesh* (Figure B). A mesh is similar to a point cloud, but instead of using only single points (or vertices) it groups each vertex with edges (straight line segments) that combine to form faces (flat surfaces enclosed by edges) that describe the shape of a 3D object. STL files, which are commonly used for 3D printing, are made of triangular meshes.

123D Catch, for instance, works by analyzing a group of 20–40 images of an object taken from different angles. (The analysis for 123D Catch is performed in Autodesk's cloud-based systems.) By performing image analysis on the photos, 123D Catch is able to isolate an object in the photos, and create a 3D mesh from the collection of photos.



Excerpted from *Getting Started with MakerBot* by Bre Pettis, Anna Kaziunas France, and MakerBlock, new from MAKE and O'Reilly, item 9781449338657 from Maker Shed (makershed.com).



“This is all experimental. There is no ‘way.’”

—Bre Pettis

LIMITATIONS

The limitations of 3D scanning depend on what technology is being used. For example, optical scanners have trouble scanning transparent or shiny objects, and digitizing probes can only scan the top surface of an object. All of the software programs discussed here have their own strengths and weaknesses.

What software you use to scan your model depends on the size of the model and your computer's hardware configuration. Two popular applications are 123D Catch and ReconstructMe — we'll show you how to use both of these. Each of these scanning packages has its own set of advantages and limitations. Thanks to these free programs, you no longer need to spend big bucks to get printable scans.

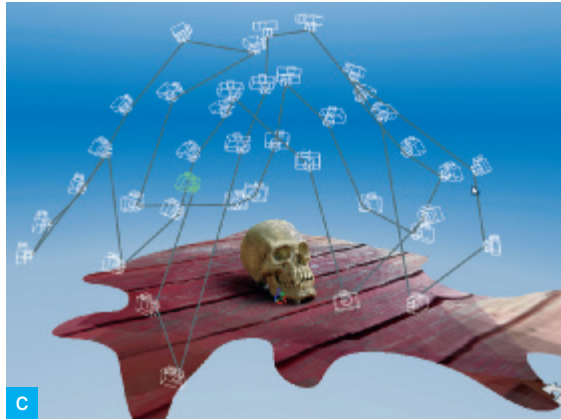
123D CATCH

123D Catch is a free application from Autodesk that enables you to take photos and turn them into 3D models. It's available as a web-based application, an app for the iPad and iPhone, and a desktop application for Windows. It works by taking multiple digital photos that have been shot around a stationary object and then submitting those photos to a cloud-based server for processing. The cloud server uses its superior processing power to stitch together your photos into a 3D model and then sends the model back to you for editing. You can download or access 123D Catch from 123dapp.com/catch.

TAKING PHOTOS WITH 123D CATCH

Your first step after planning out your project is to methodically take pictures of the object you want to Catch.

Provide enough information. You'll need to provide enough information with your pictures for the reconstruction software to create a model. Rotate around your object, capturing a frame every 5–10 degrees (**Figure C**). The goal is to get least 50%



123D CATCH TIPS

The quality of the scan that you receive from 123D Catch is dependent on the quality and consistency of the photos you provide. Here are some tips on how to select objects to Catch and how to plan out your Catch so that you obtain desirable results.

Objects to avoid. When choosing objects to scan using 123D Catch, avoid reflective surfaces, objects with glare, and mirrored or transparent surfaces. These objects won't work well for generating 3D models. For example, windows that are reflecting light will appear warped or bowed, like fun-house mirrors. Transparent objects like eyeglasses will appear as holes.

Plan of attack. Before you start a capture project, plan out the order in which you'll take your photos. It's also important to decide on a focal length. If possible, position the object that you want to Catch on a table that you can move around easily and

remain equidistant from the object at all angles. Planning out how you'll approach your subject is key when using 123D Catch.

Mark your territory.

Consider using some sort of marking system when your subject lacks discernible features or is highly symmetrical. 123D Catch has trouble with symmetrical objects; markers will help the application to register different sides of the object. You'll need 4 points for registration between any one image and 3 other images in the collection. Consider placing high-contrast tape or sticky notes on a large object. Place enough markers so that at least 4 are always visible from any of the positions you plan to shoot from.

Utilize background

objects. When possible, utilize background objects around the object you're capturing. This will help the software parse depth. 123D Catch does not like a blank wall background with flat paint. Do not attempt

to Catch objects on a flat-colored surface, like a white tablecloth. You'll get better results by using a background with patterns that help the 123D Catch software clearly differentiate between the object you're attempting to capture and the surface it's resting on.

What kind of camera?

Point-and-shoot cameras, like those in a regular digital camera, phone camera, or iPad, have been reported to take the best captures. We've been getting great Catches using an iPhone 4S. You can choose the resolution quality of your model when you upload your captures. 3MP or higher will work well. Higher-resolution photos aren't needed and will be compressed down to 3 megapixels by the 123D Catch cloud server.

Watch the Autodesk 123D Catch tutorials.

For video tutorials and tips, visit 123dapp.com/howto/catch.

overlap between images. Move the camera at regular intervals and in a predictable pattern (from left to right and from top to bottom). Make sure each point in your object is appearing in at least 4 shots. If your photos don't have enough information, your scan may have a solid block of mass where there should be empty space, or a gaping hole where there should be mesh.

Fill the frame. Try to fill the camera frame with your image (Figure D); don't lop it off or shoot from too far away. It's helpful to work consistently from high to low, and from left to right. This will help you identify errors (should they occur) later after the models are created. Once you start capturing frames, avoid zooming in or out. Zooming distorts your capture and may make it impossible for the application to align your images.

Uniform light. Make sure there's uniform light around the thing you're trying to Catch. Avoid overexposing or underexposing your images, as they hide the features you're trying to capture.

Direct light alters the exposure by creating shadows and reflective spots. The more consistent the exposure of the photographs, the more consistent your model. We find that many of our best Catches were shot on overcast days or at dusk. Consider planning your outdoor catches around these light conditions for best results.

Maintain depth of field, focus, and orientation. Blurry images won't produce accurate Catches, so retake any blurry photos before submitting them for processing. On the iPhone/iPad, you can review and retake images before submitting. If you're using a digital camera, make sure to review your images before leaving the scene of the Catch.

In addition your images must have a consistent "depth of field." If you're focused on the item that you're Catching and the background is blurry in your photos, keep this consistent throughout the shoot. Also keep the orientation of the photos consistent. Choose either portrait or landscape and stick to it.

How many pictures? More pictures are not necessarily better. What's important are the regular intervals and the capture of the overlapping angles of the object. Too many pictures will take much longer to process and if they're not capturing the object uniformly,



NOTES

If you're using a digital camera with exposure controls, you can use the following settings to minimize exposure problems:

- » AV mode (aperture priority) to lock the f-stop
- » M mode (manual) for complete control
- » Shutter speed should be 1/60 second or faster

Some phone cameras, like that in the iPhone 4S and 5, have built-in exposure controls. If you're using the 123D Catch iPhone app, try tapping the screen to set the focus/exposure before taking each capture. We're getting great results with the camera in the iPhone 4S, as it controls the exposure quite well.

WARNINGS

Capturing both detail and the entire object can be tricky. Sometimes on large objects, like statues, it's not possible to get both very fine detail and the entire object. You may need to capture the fine detail in a separate Catch. You'll need to experiment. Occasionally, we've had Catches done this way completely fail on the iPhone app, and a large white X appear after processing.

Because it can take some time to see how your catch turned out, always do one or two catches of an object that you won't be able to return to, just in case the first one doesn't complete.

If your Catch fails, consider capturing the entire object in one scan and then creating a new scan with the camera zoomed in on the fine detail.

Don't be discouraged if your first few catches don't come out as planned. Keep practicing and you'll quickly get a feel for the process and how to minimize problems.

Don't edit or crop photos before uploading! Any size, color, or tone alterations will confuse the reconstruction software and lead to less than optimal results. Upload your photos to the cloud server as they were originally taken.

“By taking a whole series of close-up pictures just at one level, I got really good 3D detail. Really good reproduction of very, very small depth.”

—Michael Curry (aka Skimbal), Thingiverse superstar



NOTES

In the Windows desktop or online application, you can select all your images and upload them at once.

The Windows 123D Catch desktop app has additional editing options. If your automatically generated files have missing sections or errors, you can edit it using the app's photo stitching options. When you open the application, select Create an Empty Project, then login through the application and navigate to My Corner in order to access, download, and edit your scans. Refer to the tutorials at 123dapp.com/howto/catch for how to manually stitch photos.

will still produce poor results. The optimal number has been reported as somewhere between 20–55 photos, depending on the object. If you're using the iPad or iPhone, you're limited to 40 images.

Capturing detail. If you need to capture fine details, first capture the entire object at a distance that fills the frame. After you've completed a full sweep of the entire object, then move in and capture the details. Make sure you maintain the 50% overlap between the distance photos and the detail photos, so that the software can still stitch the photos together. Be careful when transitioning from shots of the whole model to detail shots. Make sure to have transition photos that capture 50% overlap between the transitions. Don't suddenly zoom in on the detail, as this will produce poor results or cause your scan to fail.

UPLOADING YOUR PHOTOS TO THE CLOUD

Take your photos using the process outlined above and then submit them to 123D Catch via your application of choice. How you do this depends on how you took the photos.

iPhone or iPad application: Submit the photos via the iPhone/iPad app (Figure E). The app will inform you when it has finished processing your scan, or *photoscene*.

Windows desktop application: Load your photos onto your computer from your digital camera or phone. Then open 123D Catch and select Create a New Capture. A login window will open, and you'll need to log into your Autodesk account (or create one).

Next, a new window will open to enable you to locate your photos on your computer and upload them. Those photos will then be submitted for processing.

After your photos have been uploaded, click Create Project. You may need to register the desktop application, if you haven't already. A dialog box will then ask you to name, tag, and describe your capture. Fill out the form completely and click Email Me. (You can select Wait instead, but it may take some time, depending on the number of photos and the server availability.)

Browser-based application: Load your photos onto your computer, then go to apps.123dapp.com/catch to upload them. After going through the welcome info, select Create New from the menu. Then click Add

Images to locate and upload your images to the cloud server.

After your photos have been uploaded, click Finish. 123D Catch will ask you to sign in (or create an account) and then begin uploading your photos.

After the photos are uploaded, you'll need to title, tag, describe, and select a category for your Catch. Then click Create Model. Your photos will then be submitted for processing.

It can take some time for the 123D Catch cloud server to process your photos, but you don't have to wait around. They'll email you when your scan is ready.

DOWNLOADING YOUR MESH

Once your photoscene is available, you need to retrieve the file in an editable format.

Go to 123dapp.com/MyCorner and log into your account. Regardless of your upload method, your processed scans will be there under Models and Projects.

Click on a project to open it, then scroll down to the Downloads section. You can download the STL file, a "mesh package" containing a textured OBJ file that looks like your photoscene, or the images you used to create the scan.

The STL will often be named *viewable.stl*. If this file is available, download it.

However, sometimes there will only be a zipped mesh package. If this is the case, you can convert the OBJ file to an STL using MeshMixer, MeshLab, Netfabb, or Pleasant3D (see page 98).

While there are some editing tools in the online and desktop versions of 123D Catch, they're not yet well suited to preparing models for 3D printing; it's difficult to slice off sections. Instead, edit your mesh using the techniques described in "Cleaning and Repairing Scans for 3D Printing" on page 98.

RECONSTRUCTME

ReconstructMe is a 3D reconstruction system that gives you visual feedback as you scan a complete 3D model in real time. It works with the Microsoft Kinect (Xbox and PC versions) and the Asus Xtion Pro. ReconstructMe is Windows-only software and you need a high-quality video card to make it work. Currently there is both a free noncommercial version and a paid commercial version of the software. ReconstructMe is excellent for scanning larger objects, such as people, but not great for small objects with fine detail.

ReconstructMe is currently the easiest way to get quick and complete scans, but there are a few unavoidable limitations that come with this type of realtime scanning.

First, ReconstructMe is Windows-only, but can be run cross-platform using virtual machines or Boot Camp on a Mac. You also need a fairly high-end graphics card to run the software. It's also picky about the version of OpenCL (a computer library that can run instructions on your graphics adapter) installed on your machine. ReconstructMe is constantly being updated, so refer to the documentation and video card specifications at reconstructme.net/projects/reconstructme-console/installation.

INSTALLING RECONSTRUCTME

Download ReconstructMe. Go to reconstructme.net/projects/reconstructme-console and download the appropriate version for your Kinect (for Xbox or for Windows) or your Asus Xtion Pro or Pro Live.

Download the dependencies and drivers. In order for ReconstructMe and the other drivers to work, you'll need OpenCL. This means you'll have to update your display and CPU drivers to the latest version for your installed Nvidia, AMD, or Intel graphics card.

You will also need the C++ Redistributables from Microsoft Visual Studio 10 installed, as well as the appropriate driver package for your device. See reconstructme.net/projects/reconstructme-console/installation for the necessary links for the software dependencies.



KINECT VS. ASUS XTION

As soon as the community cracked open the Kinect and made it do things it wasn't intended to do, 3D scanning was one of the first items on the list. As wonderful and disruptive as the Kinect was, it wasn't the only device of its kind. In fact, other folks brought the exact same technology to market. Scanning with the Kinect is powered by hardware developed by an Israeli company, PrimeSense. PrimeSense released a software development kit (SDK) called OpenNI (Open Natural Interaction)

that some people, such as the folks behind ReconstructMe (Profactor GmbH), have used to develop awesome software tools for Kinect. And the great thing about this is that their software can be made to work with other hardware that uses the PrimeSense technology.

One such piece of hardware is the Asus Xtion (\$160), which has some advantages over the Kinect:

1. It's much smaller (about half the size).
2. It's lighter (half a pound).
3. It doesn't require a separate power supply (it can be powered over the USB connection).

The Xtion has some disadvantages, though:

1. It's more expensive than Kinect for Xbox (\$110).
2. It doesn't work with all software written for Kinect.
3. It doesn't have a software-controlled motor (the Kinect has one you can use for moving the camera around). Still, if you're looking for a portable depth camera for 3D scanning, the Xtion is well worth considering.

INSTALLING RECONSTRUCTME ON A MAC WITH A VIRTUAL MACHINE

You can install ReconstructMe on a Mac without using Boot Camp, by running Windows on a Parallels or VMware Fusion virtual machine, in the same way you would install it on Windows, with one exception. You won't be able to install your graphics drivers for the virtual machine by downloading an update from the manufacturer. You'll need to install OpenCL support separately. You can get the OpenCL CPU runtime for Windows from Intel at software.intel.com/en-us/vcsourc/tools/opencl-sdk.

NOTE

If you're an early adopter who installed an early version of ReconstructMe and now wish to upgrade, make sure to remove the old drivers before updating. If you fail to do this, ReconstructMe will continue to find and use the old drivers and repeatedly crash.

If you go this route, you won't be able to perform a live scan. Instead, you'll need to first record your subject with the ReconstructMe Record tool, then complete the scan with ReconstructMe Replay.

Installing ReconstructMe on virtual machines is experimental, so "your mileage may vary." We were able to run ReconstructMe on Windows 7 using Parallels 7. However, we were not able to install OpenCL on VirtualBox 4.2.1.

TIPS FOR RECONSTRUCTING YOURSELF (OR SOMEONE ELSE)

Once you have ReconstructMe installed, refer to the manual at reconstructme.net/projects/reconstructme-console/usage for how to launch the application. There are several different resolutions and modes available for scanning with ReconstructMe and new features are being added all the time.

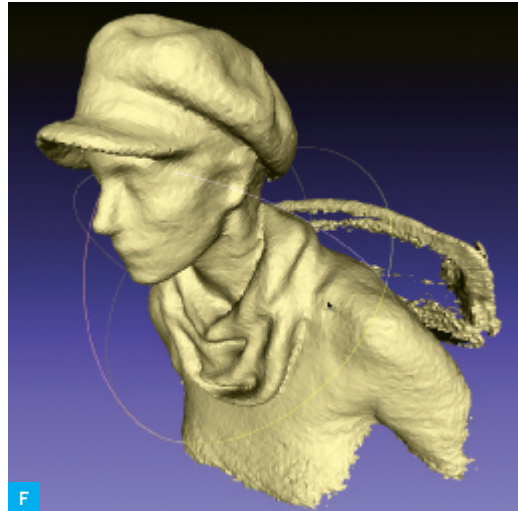
When starting ReconstructMe, make sure you scan using the correct mode for your sensor. Check the company's Device Compatibility Matrix at makezine.com/go/rmmatrix to see if your graphics card is capable of running the high-res version. If it isn't, the program will crash.

If you experience crashes in both the standard and high-res modes, you may need to run the ReconstructMe Record tool. After saving your scan, you can play back the recording with ReconstructMe Replay and save your file as an STL.

After you have ReconstructMe up and running on your machine, here are some basic tips for scanning people.

1. Sit in a spinnable office chair.
2. Position your Kinect or Xtion so that only your upper body is visible in the scan area.
3. Slowly, spin yourself around in the chair while keeping your upper body in a static position.
4. Save the file as an STL — and make sure to do it after you finish your capture, while the console is open, or you'll lose your scan.
5. If your graphics card or memory constraints are causing the program to crash, try using the record feature to record your scan and then playback to reconstruct the mesh.

After saving the STL, open it up in MeshLab or Pleasant3D and take a good look at it (**Figure F**).



F

TIP

When scanning yourself, sit with your back to the Kinect with your computer in front of you. That way your arm movements won't be captured when you press the keys on your computer to start and end the scan.

NOTE

All our ReconstructMe scans were done using Boot Camp on a mid-2010, 15-inch MacBook Pro running OS X 10.8.1 (Lion) with a 2.66GHz Intel Core i7 processor and 8GB of memory.

The graphics card was a Nvidia GeForce GT 330M 512 MB. With this configuration, we were able to run realtime reconstruction mode, but unable to run the high-resolution setting for ReconstructMe. The lack of definition in the facial features in the scan reflects these constraints. However, ReconstructMe is excellent at capturing folds in fabric, so I wore a hat and scarf during the scan to make up for the lack of facial definition. Other smooth fabric items like shirt collars, ties, and smooth hair are also captured well.



GET A HANDLE ON IT

If you're scanning other people or things, a Kinect handle (thingiverse.com/thing:18125) or a Kinect tripod mount (thingiverse.com/thing:6930) can come in handy.

CLEANING AND REPAIRING SCANS FOR 3D PRINTING

Use powerful, free mesh editing software to make your scans print-ready.

WHILE IT IS BECOMING EASIER TO CREATE HIGH-QUALITY SCANS, CREATING VALID INPUT FILES IS SOMETIMES DIFFICULT. Before you can print your 3D scans, you need to clean up, edit, and repair the files to make them printable.

The most common problems with 3D scans are:

- » holes
- » disconnected parts
- » “junk” captured from the environment around the model or used to map the object in space, but not part of the model
- » open objects with faces that aren’t closed.

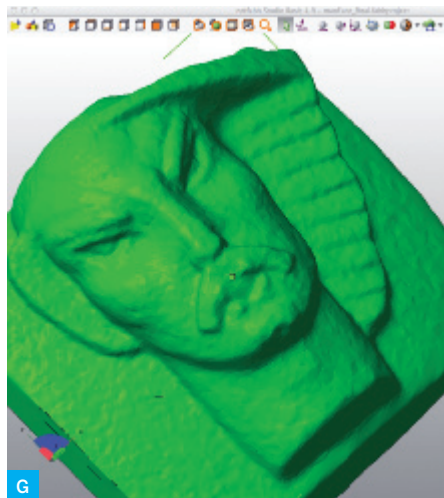
However, analyzing STL files for errors and buildability has never been easier.

Each of the following software packages has strengths that, when used together, can make it simple to edit and print great-looking scans.

Netfabb (netfabb.com) enables you to view and edit meshes and provides excellent repair and analysis capabilities for your STL files. Netfabb makes it easy to slice off bits of jagged scans and quickly repair those scans. In most cases, you’ll want to slice off the bottom of your model to create a flat surface against the build platform.

Netfabb is available as a desktop application (**Figure G**) and a cloud service. It’s also available as an STL viewer with a connection to the cloud service on the iPhone. Netfabb Studio is available in both a Professional and a (free) Basic edition. It runs on Windows, Linux, or Mac.

Autodesk MeshMixer (meshmixer.com) is great for mashing up individual meshes together into a new model. It works well for smoothing out bumps, blobs, and other strange artifacts that can show up in scanned files (**Figure H**). It’s also an excellent tool for

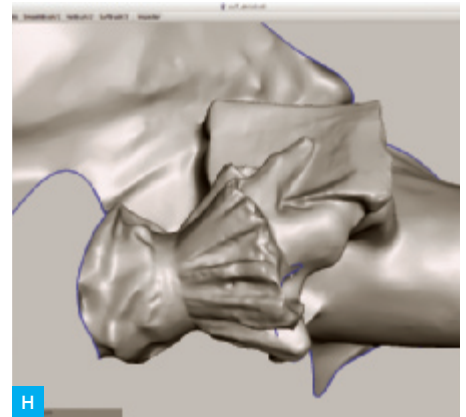


Netfabb rendering of 123D Catch scan of a stone face from a fountain.

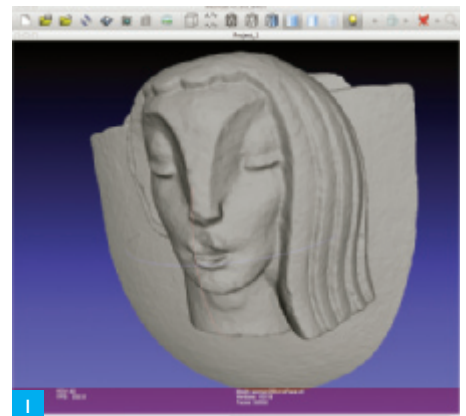
“capping” models that are missing a side/top/bottom to make them manifold.

MeshLab (meshlab.sourceforge.net) has a variety of functions that can be used to repair and edit meshes, but the Poisson filter to smooth out surfaces is the most useful for cleaning up scans for printing. Because it’s easy to rotate meshes by dragging them around with the mouse, it also makes an excellent STL viewer. It’s available as a cross-platform desktop application (**Figure I**) and as a 3D model viewer for iOS and Android.

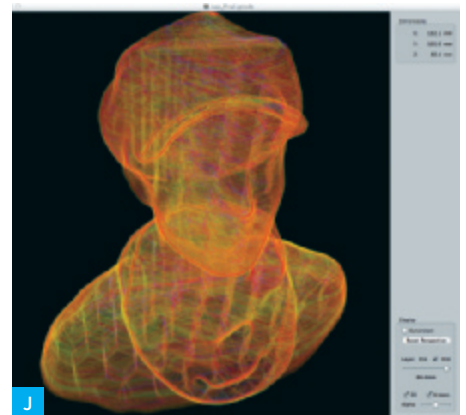
Pleasant3D (pleasantsoftware.com/developer/pleasant3d) is a great Mac-only application for resizing STL files by specified units (as opposed to scaling in MakerWare or ReplicatorG). It can also convert ASCII STL files into binary STL format. It also shows G-code visualizations (**Figure J**), which can be helpful for previewing how your model will print. Pleasant3D also makes a fast STL viewer and is great for quick STL previews.



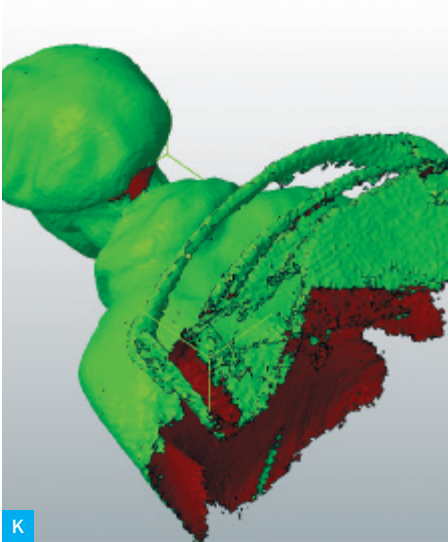
MeshMixer rendering of 123D Catch scan of a hand detail from a statue.



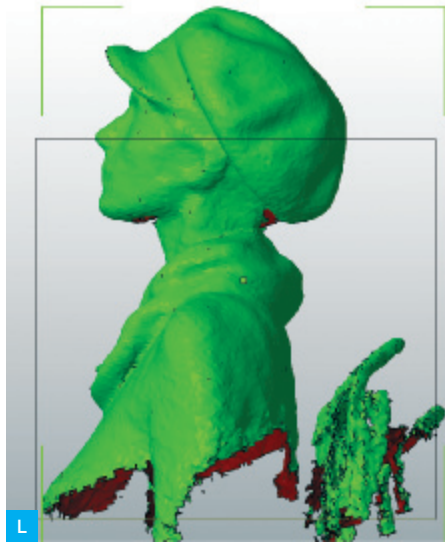
MeshLab rendering of 123D Catch scan of another face from a fountain.



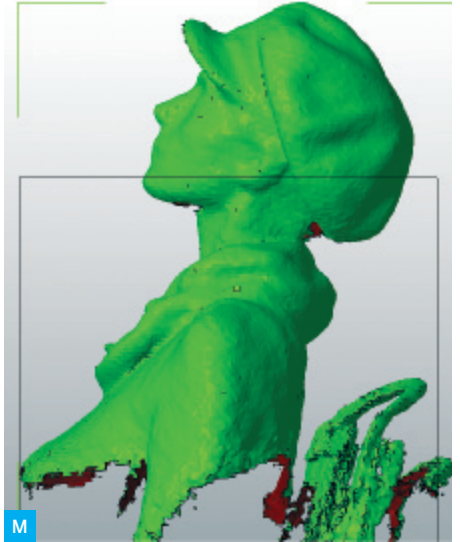
G-code visualization of a ReconstructMe scan in Pleasant3D.



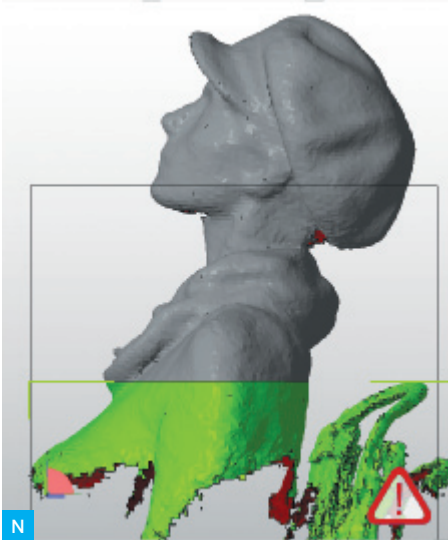
K



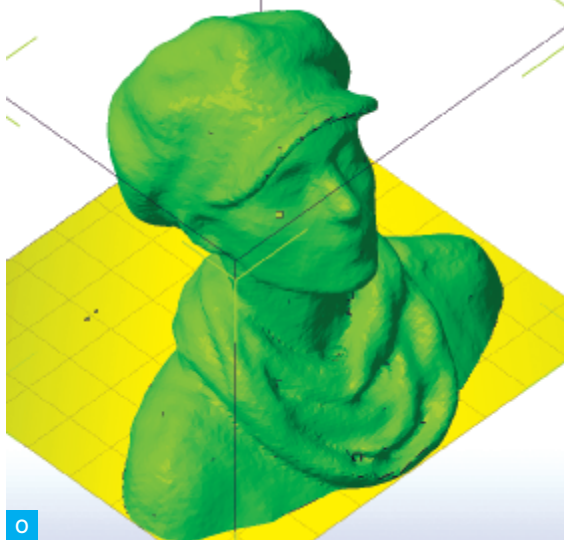
L



M



N



O

NOTES

To pan in Netfabb, use Alt + Mouse Drag.

The model shown has a severe chin underhang (an overhang greater than 90°). You should try to minimize this when creating your scan. The back of the head where the hat juts out also has a severe overhang. External support material was used to help with the overhangs when printing the hat back. Support was not used under the brim and chin, but they still printed OK!

REPAIRING MOST SCANS

Most scans that you create using the software programs described here will have a mesh that's mostly complete. However, these scans will usually have holes, junk, and other issues that you'll need to edit. Here's how to do it.

(If your scan is missing large areas of mesh and has huge gaping holes, or is just the front or "relief" of a building or sculpture, you can use MeshMixer to "cap" it — see page 102.)

REPAIR AND CLEAN UP IN NETFABB

Open Netfabb Studio Basic and open the STL file of the model you created using ReconstructMe or 123D Catch, by selecting

Project → Open from the menu (Figure K).

To help you see your model's orientation, select View → Show Platform. If you can't see the yellow platform, then you may need to zoom out.

Next, you need to re-orient the model:

» To move the part to the origin of the platform, select Part → Move, then select the To Origin button from the dialog box and click Move.

» Now zoom in on your model by selecting View → Zoom To → All Parts.

» Click on the selection tool (it looks like an arrow). Click on the model to select it, then move the selection tool over the green corner that appears around the model.

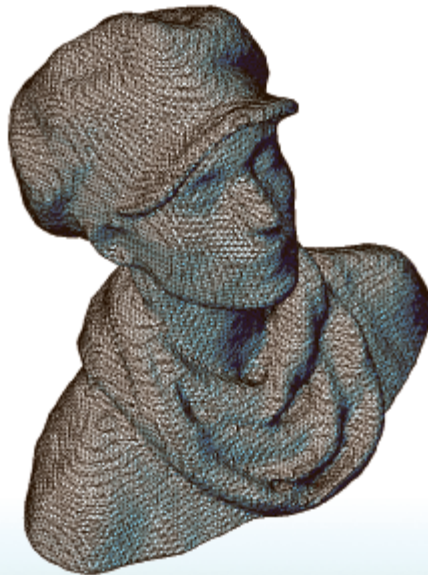
» When the selection tool is over the green corner bracket, it will appear as a rotation symbol. Rotate the model, tilting it so

the head is pointing up and the body is pointing down toward the platform (Figure L).

You'll have to change your view and rotate the model several times in order to orient it on the platform. Try to place the model so the shoulders are at equal height. You can change your view from the View menu or click on the cube faces in the main toolbar at the top of the screen. Align the model within the "box" relative to the platform.

Make sure to tilt the head back using the Rotate tools to help with the overhang that can develop under the chin of a person (Figure M). MakerBotters call this the "45 degree rule": avoid overhangs greater than 45 degrees, to minimize droopy loops of extruded plastic.

Use the Cuts tools on the right of the screen to cut a flat bottom for the model.



» Look at all those triangles!

Drag the Z slider so that the bottom of the blue cut line is cutting off the jagged edges of the scan, and select the Execute Cut button. Then select Cut.

You can then click on the part of the cut model that you want to remove. The selected part will turn green (Figure N, page 99).

Go to the Parts section that's now displayed in the top right-hand corner of the screen. Click the X next to the part you want to remove (the jagged parts of the scan) to delete the part. Netfabb will ask you if you really want to remove it. Click OK.

You'll now have a nice clean edge at the bottom of your model. Move the part to the platform (Figure O) by selecting Part → Move, then select the To Origin button from

the dialog box and click Move.

Next we'll repair the holes in the model. There's probably a large hole under the chin where the scanner couldn't gather information and likely a hole in the top of the head.

Select the Repair tool (it looks like a red cross). The model will turn blue and you can see the triangles in the mesh (Figure P). There will be yellow spots where repairs are necessary. To repair the model, click the Automatic Repair button. Then select Default Repair from the dialog box and press the Execute button. Netfabb will ask you if you want to remove the old part; click Yes.

Then click the Apply Repair button at the bottom of the right side of the screen. In the dialog box that opens, select Yes when

asked if you want to remove the old part.

Save your project as a NetfabbProject, in case you want to edit it later, using Project → Save As.

Export an STL file using Part → Export Part → STL. Netfabb may warn you that there are issues with your file. If you see a big red X when you attempt to export your model, click the Repair button on the dialog box. The X will become a green checkmark. Then click Export to save the STL.

SMOOTH THE SURFACE IN MESH LAB

Sometimes you want a smooth surface on a model so it makes a smooth, shiny print. MeshLab has a Poisson filter that will nicely smooth out your mesh.

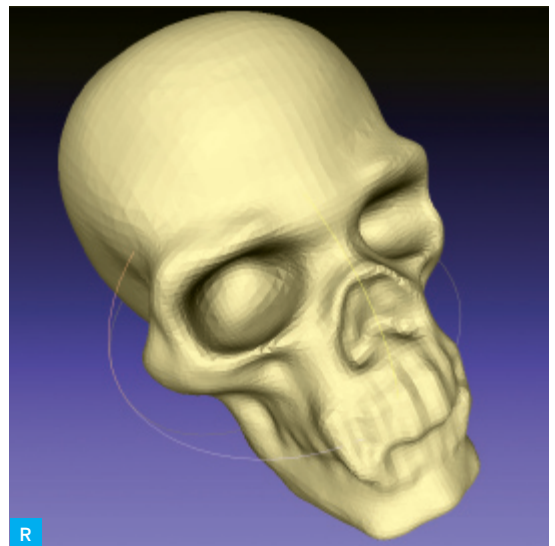
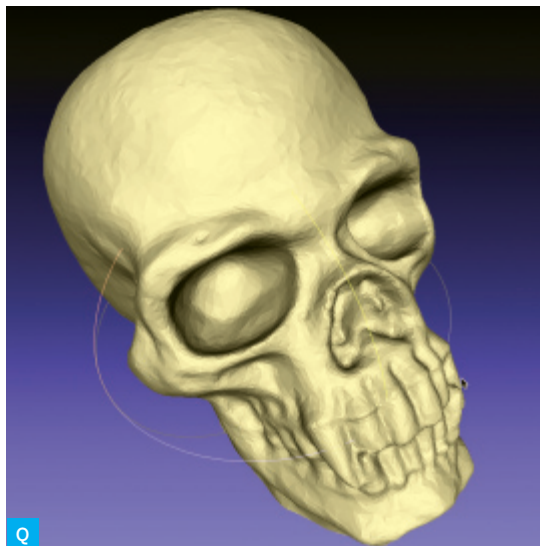
If you're able to create a high-resolution scan from ReconstructMe, you may want to smooth it out a little for printing. For normal-resolution ReconstructMe scans, skipping this step will allow you to keep more detail in the model.

To smooth the surface, open MeshLab and create a new project from File → New Empty Project. Then select File → Import Mesh to open your STL file in MeshLab. When the dialog box pops up that asks you if you want to "unify duplicated vertices," click OK.

In MeshLab, you can drag the model around with the cursor to get a good look at it. Go to the View menu in the top toolbar and select Show Layer Dialog.

Now select Filters → Point Set → Poisson Filter → Surface Reconstruction Poisson. In the dialog box, set Ochre Depth to 11. (The higher number the better; "good" is 11 — but

The original mesh shown in MeshLab (left). After applying the Poisson filter and hiding the original mesh (right).



if you go any higher than 11, MeshLab will crash.) Click on Apply. You'll see visible smoothing on the surface of the model.

After applying the Poisson filter, there will be 2 layers: one with the original file you imported (Figure Q) and one labeled Poisson mesh. Click on the green "eye" icon of the filename to hide the original file and keep the Poisson mesh (Figure R).

Save it as an STL file. Go to File → Export Mesh As. Use the default export options.

REMOVE BUMPS AND BLOBS IN MESHMIXER

Depending on how your scan came out after repairing and (optionally) smoothing, you may want to remove some bumpy areas or blobs that are on your model. If your model needs no additional smoothing, you can skip this step.

Open MeshMixer and import the STL file. Select the Smooth Brush from the top navigation. Use the mouse wheel to adjust brush size, or you can adjust it in the menu on the right side of your screen.

Click and drag on the bumpy or lumpy areas on your model to smooth them out (Figure S). When you're satisfied with the appearance of your model, export the file as an STL.

FINAL CLEANUP/REPAIR IN NETFABB

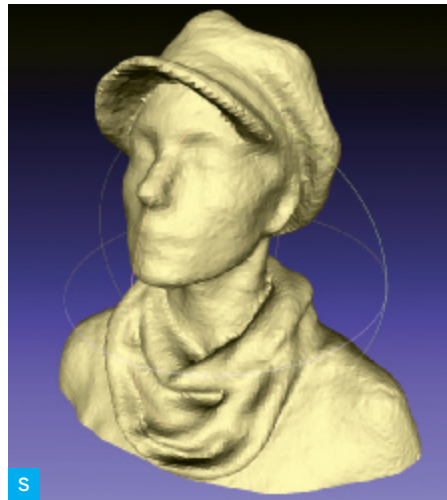
Open the STL back up in Netfabb. If you used the Poisson filter in MeshLab, the formerly smooth bottom of your model will be bumpy. To fix this, re-slice the bottom off your model to make it flat.

Repair the model and export as an STL (Figure T).

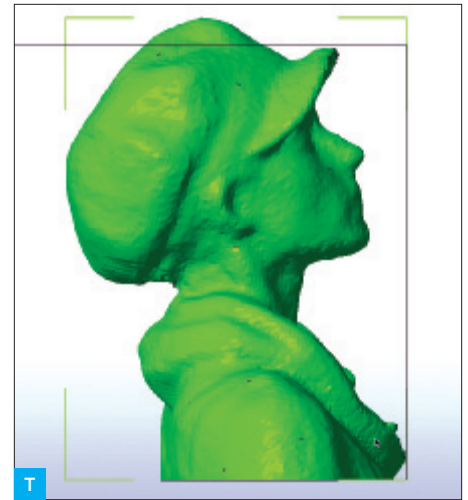
PRINT YOUR MODEL

Your scan is now cleaned, repaired, and ready to print! Open it in MakerWare or ReplicatorG (or the equivalent software for your printer), then resize or rotate if necessary and print it out (Figure U).

■ Tony Buser created the seminal video tutorial (vimeo.com/38764290) that deeply informed this chapter of our book.



S



T



U



U

REPAIRING RELIEF SCANS BY CAPPING

SOMETIMES YOU HAVE A MESH OF A BUILDING OR SCULPTURAL RELIEF THAT'S MISSING A SIDE, TOP, OR BACK

and you need to create a closed model by “capping” the object so you can print it. Meshes generated from 123D Catch scans often have these issues when you’re only able to scan the front part of a large object. MeshMixer and Netfabb can easily help you fix this problem, as well as filling minor holes or removing disconnected parts.

MeshMixer doesn’t have any labeled controls for panning and zooming around your model — you need to hold down key combinations while dragging your mouse/trackpad. Here are the basics (see also meshmixer.com/help):

Basic MeshMixer View Controls

- » Alt + Left Click: orbit camera around an object
- » Alt + Right Click: zoom camera
- » Alt + Shift + Left Click: pan camera

FIXING HOLES, NON-MANIFOLD AREAS, AND DISCONNECTED COMPONENTS

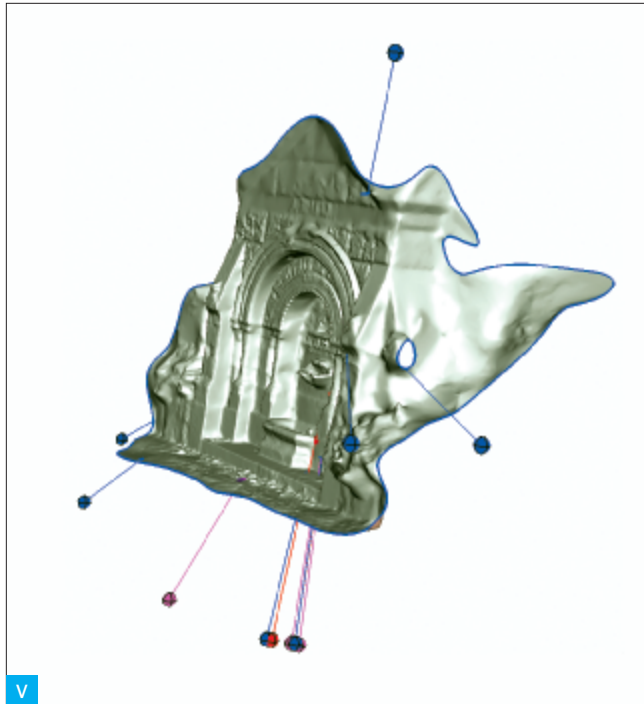
We’ll attack each problem in turn. First, we will address the holes, non-manifold areas, and disconnected components.

Open MeshMixer and import your STL or OBJ file. The model shown here is a fountain, photographed from the front for 123D Catch. You can see the original Catch and grab the STL and OBJ mesh files at 123dapp.com/stl-Catch/Gothic-Fountain/849545 to follow along.

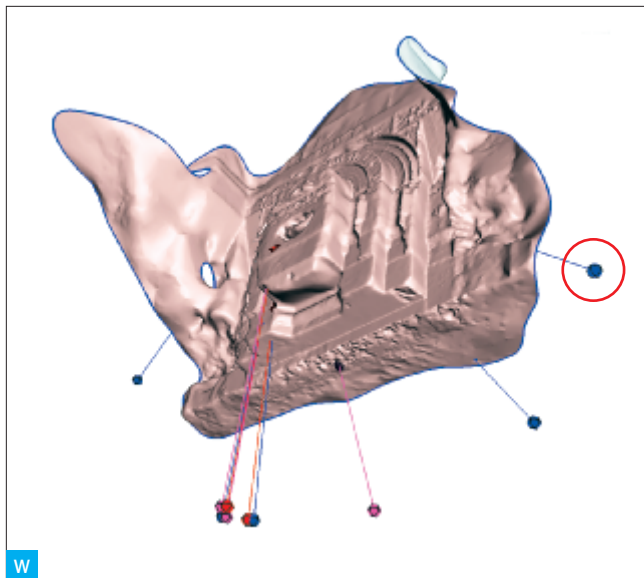
On the “Action Bar” menu at the top, click the Inspector button. Your model will now have a number of colored spheres attached to it (**Figure V**):

- » Red spheres represent the non-manifold areas
- » Magenta spheres represent the disconnected components
- » Blue spheres represent holes

Orbit around your model (Alt + Left Click, drag your mouse) to identify which blue sphere is directly on the blue outlined edge that represents the large hole in the model that we want to cap. (Here we want to cap the back of the fountain.) Take note of this particular sphere (circled in **Figure W** for



V



W

TIP

If your model has a lot of extra “junk” in it, slice it off in Netfabb before editing it in MeshMixer.

NOTE

When repairing meshes with large holes or missing areas, don’t click AutoRepair All, as this can cause the program to immediately crash. In addition, you want to close the back of the model yourself, because you want to control how it’s closed. You don’t want a big auto-repaired blob, you want a smooth cap.

emphasis) and make sure that you edit it last. You want to close all of the other minor holes first, then cap the back of the model.

Clicking on a sphere will repair the problem. Right-clicking on a sphere will select the area and allow you to edit the selected part of the mesh. When you right-click, editing options will appear on the side of the screen.

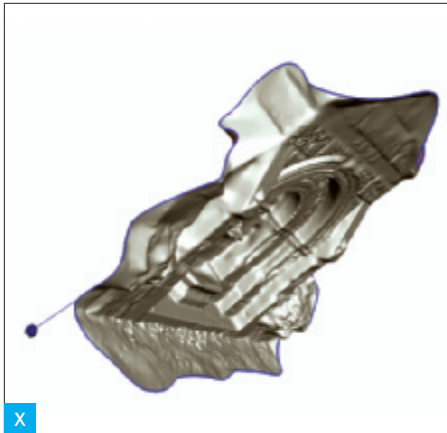
First, left-click on any red or magenta spheres to close the non-manifold areas and reconnect stray components. Each sphere and its indicator line will disappear after you click on it, indicating that the

problem is resolved.

Next, close all the holes by clicking on the blue spheres, except for the sphere that represents the large area of missing/open mesh. Orbit around the model to make sure you get them all (**Figure X**).

Next, *right-click* on the last blue sphere that represents the large area of open mesh so you can edit the mesh. The blue edges will now have a dark orange tint to them where the mesh is selected (**Figure Y**).

Next you need to smooth out the edges. From the Action Bar, select Modify Selection



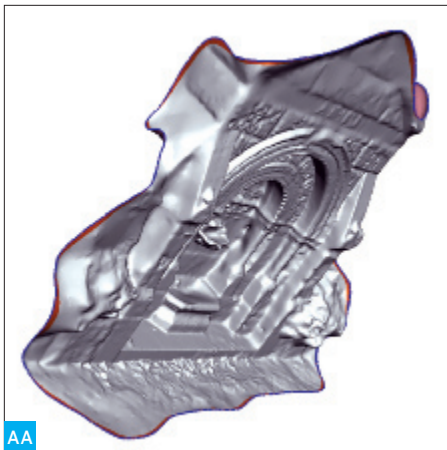
X



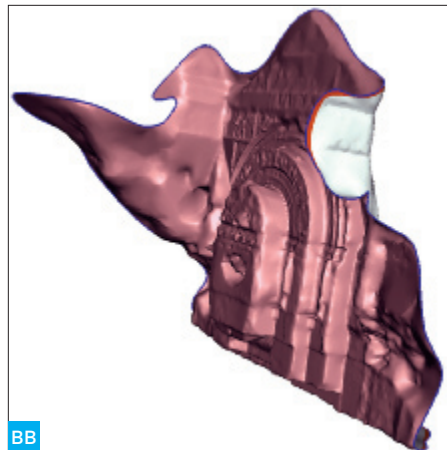
Y



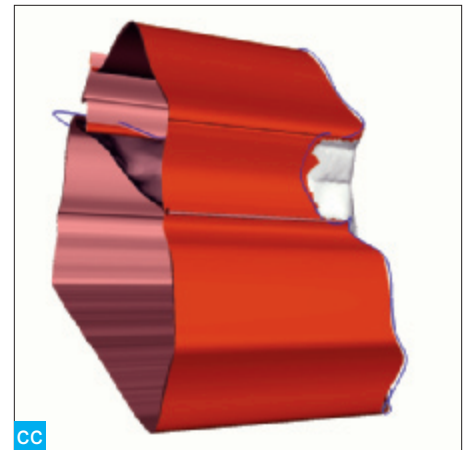
Z



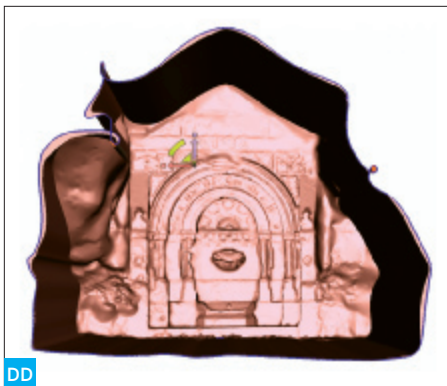
AA



BB



CC



DD



EE

NOTE

Mesh selections in MeshMixer stay selected until you manually click the Clear Selection button from the top menu.

WARNING

Sometimes MeshMixer will crash when scaling the extrusion. It will usually allow you to open the model again. Save often in the default MeshMixer .mix format to ensure that none of your changes are lost.

→ Smooth Boundary. Smoothed areas will be highlighted (Figure Z); click Accept to accept them (Figure AA).

TO CLOSE LARGE AREAS OF MISSING MESH

First repair the model and smooth the boundary as outlined above.

With the boundary still selected, click Edits on the Action Bar, then Extrude. You may need to rotate your model to get a better view of the missing mesh area (Figure BB). After you select Extrude, an Extrusion

properties panel will open up on the right.

For your extrusion properties, choose Flat from the EndType drop-down menu. Under Offset, choose an offset number that's negative, to extrude the model backward (Figure CC). You can also drag the gray bar behind the Offset label to the left or right to change the offset. You might also need to change the Direction option to get a straight extrusion. In this example, we changed the direction to Y Axis. When you're satisfied, click Accept.

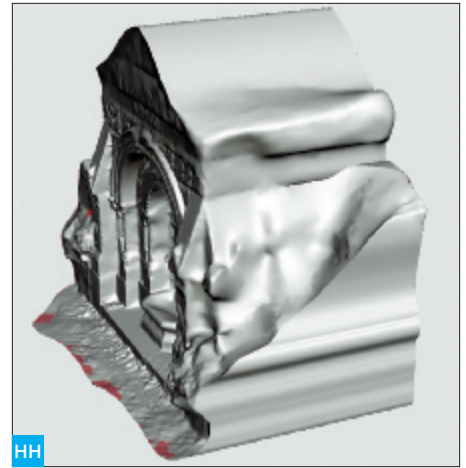
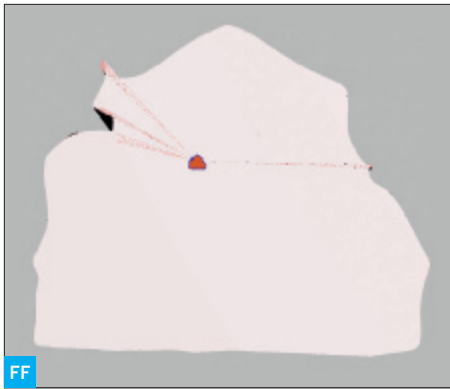
Next, on the Action Bar, click Modify

Selection and select Smooth Boundary. Then click Accept.

Rotate your model so you're looking head-on at the open area. On the Action Bar, click Deformations and select Transform Faces. Arrows in the X, Y, and Z planes will appear (Figure DD).

Scale the extrusion in by dragging the white box between the arrows. Don't close the hole yet (Figure EE). Click Accept.

Now you need to close the hole. From the Edits menu, select Erase & Fill (Figure FF, page 104). Then click Accept.

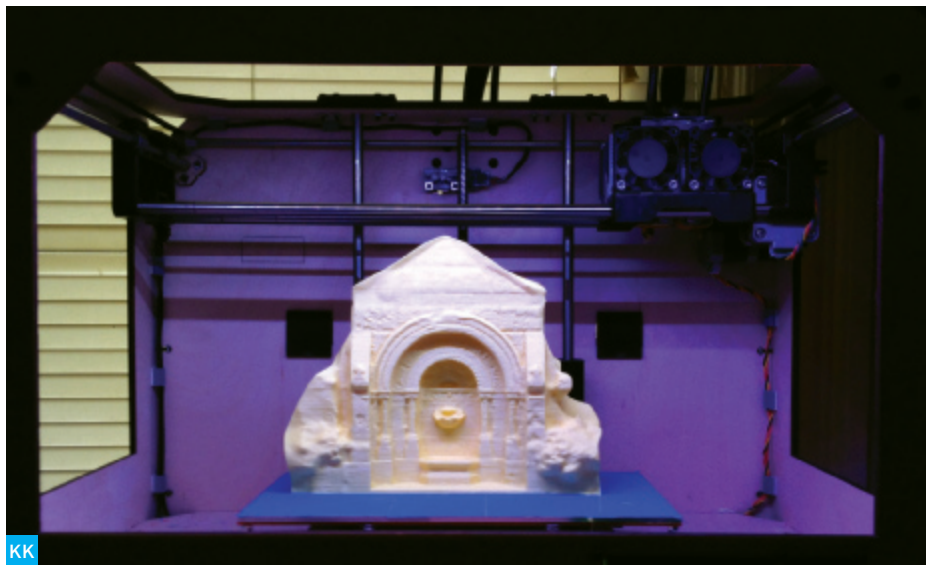
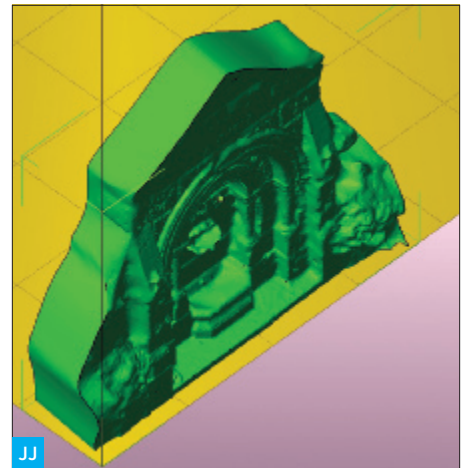
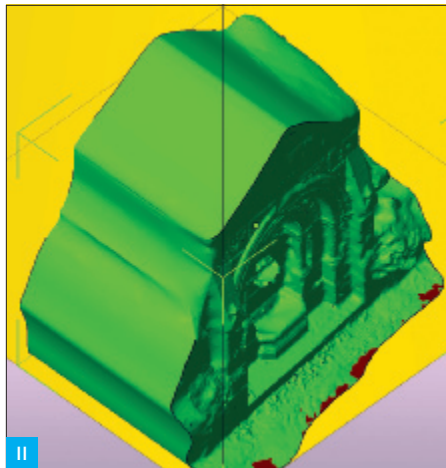


The model should be manifold and appear “capped” with a flat back (Figure GG). This model has some ridges in the roofline that occurred from extrusion that need to be smoothed out and repaired. Click on Select and click Clear Selection.

These ridges won’t smooth out with the Smooth Brush tool alone, so we need to use the Volume Brush. On the Action Bar, click on VolBrush/2 and brush options will appear. Select Brush1 and use the Flatten and Reduce brushes (mouse over them to see their names) to flatten out the bumps (Figure HH). Then use the Smooth Brush tool to soften it out.

Export your file as an STL and then open it up in Netfabb (Figure II).

As described previously in “Repair and Clean Up in Netfabb” (see page 101), slice off unwanted parts of the model, repair the mesh, and then export it as a binary STL (Figure JJ). Your model should now be capped, cropped, and ready for printing (Figure KK).



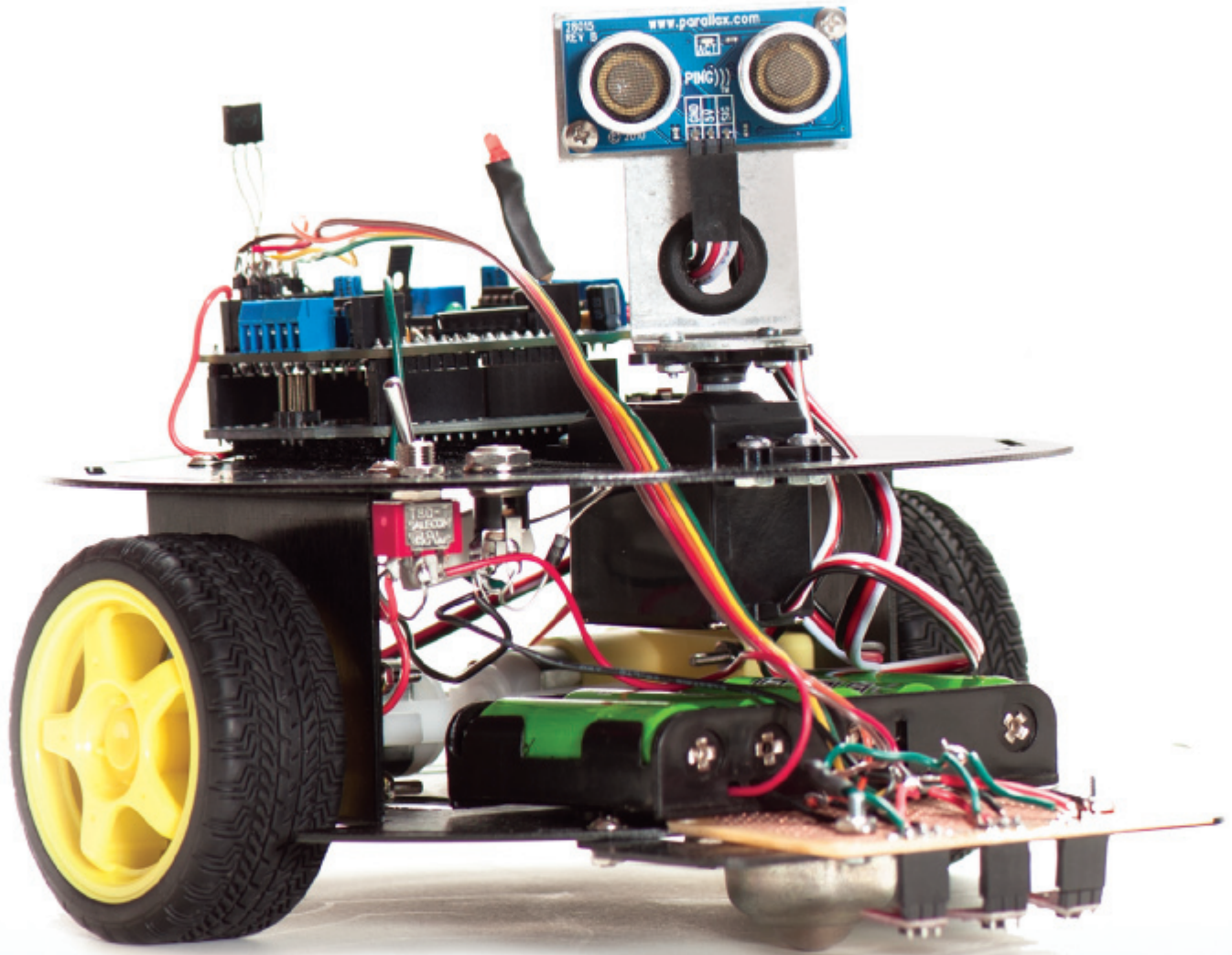
SCAN YOUR WORLD

With the tools and techniques outlined here, you’re ready to scan anything that you can convince to sit still. And even if you end up with messy meshes, you can clean them up well enough that you should be able to print anything you can scan. It’s time to digitize the world around you.

+ All 3D models used in these tutorials are available on Thingiverse: [thingiverse.com/akaziuna](https://www.thingiverse.com/akaziuna)

Anna Kazianas France teaches the “How to Make Almost Anything” rapid prototyping course in digital fabrication at the Fab Academy at AS220 (as220.org/fabacademy). She’s also the Dean of Students for the Global Fab Academy program (fabacademy.org). Learn more about her at kaziunas.com and check out her things at thingiverse.com/akaziuna.

Meet your future robot overlord. (Cute, isn't he?)

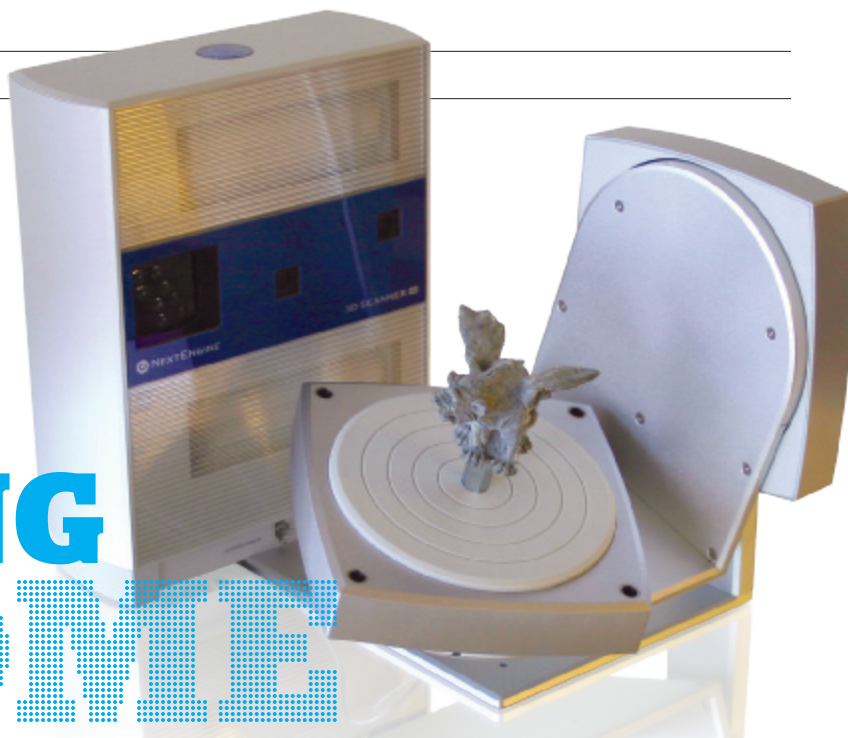


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» The NextEngine Laser Scanner represents the low end of the professional 3D scanner market at about \$3,000, not including the multi-drive subject platform shown here.

3D SCANNING AT HOME



Cheaper and easier than ever before!

► **IN DESKTOP MANUFACTURING, AS IN DESKTOP PUBLISHING, SCANNING IS THE YIN TO PRINTING'S YANG.** Whereas a printer turns data into real-world objects, a scanner turns real-world objects into data. Along with modeling from scratch, scanning — in which a real 3D object is imaged to produce a virtual 3D representation — is the other major method for making 3D models that can be printed.

Pro-grade 3D scanners are available but these can be as expensive as professional 3D printers, or even more so.

Fortunately, it's easy, almost astoundingly so, to put together DIY 3D scanners capable of very impressive results. There are three common methods: *laser-line scanning*, *structured-light scanning*, and *image-based modeling* (aka *photogrammetric modeling*).

LASER-LINE SCANNING

Perhaps the first, most popular DIY 3D scanning method involves imaging a subject under illumination with a laser-line generator. Laser-line scanning works best with a neutral backdrop, often a white 90° corner backdrop that, depending on software, is sometimes printed with a special black calibration pattern. The backdrops are not difficult to prepare, and laser-line generators are inexpensive to buy and easy to make. (One method improvises a line generator from a laser pointer and a wine glass stem:

instructables.com/id/3-D-Laser-Scanner.)

The addition of a rotating platform underneath the subject, as in the DIY SplineScan system (makeprojects.com/project/3D/98), makes it easier to scan it on all sides.

With the subject in place before the backdrop, you simply turn off the lights, turn on the camera, and “paint” the subject with the laser line from all sides. Software does the rest.

Though it's possible to use MATLAB, for instance, to extract 3D shapes from raw image data gathered in this way, since 2006 Germany's David Vision Systems has been developing a low-cost program specifically for this purpose. David Laserscanner software (david-laserscanner.com) generates 3D data in real time and allows you to watch the model developing on-screen. It can stitch together scans of the same object taken from multiple angles, and export directly to several popular 3D file formats. The latest versions support visible structured-light scanning as well. The free trial version has some restricted options and a scan resolution cap, but is otherwise fully functional.

STRUCTURED-LIGHT SCANNING

This method combines a light projector, a digital camera, and an image analysis program to produce a low-cost DIY 3D scanning system that's generally faster than laser-line scanning, and doesn't require a

special backdrop. The projector “paints” the subject with a geometric pattern, often a grid of light and dark stripes, which the software can use to infer depth by analyzing how the surface of the subject changes the shape of the projected pattern. The projected light can be in the visible spectrum or it can be at a wavelength invisible to the human eye, commonly IR.

Invisible structured-light scanning has advantages, perhaps foremost that it doesn't interfere with ambient room lighting. Microsoft's interactive motion-sensing Kinect controller, which has taken the 3D imaging world by storm, operates by invisible structured-light scanning in the IR band.

Before the advent of Kinect, visible structured-light scanning was a common DIY technique; it was used to produce much of the 3D imagery in Radiohead's 2008 “House of Cards” video, and in 2009, multimedia artist Kyle MacDonald posted a landmark Instructable that popularized the technique among DIYers (instructables.com/id/Structured-light-3D-scanning). Software options for visible structured-light scanning include David Laserscanner, as mentioned above, and ThreePhase, a basic decoder utility developed as part of the open source structured-light project. Much of the structured-light suite is written for Mac OS X, but ThreePhase runs inside the Processing IDE and works on any OS — Mac, Windows, or Linux — that can run Processing.

Since Microsoft's introduction of Kinect in late 2010, however, the DIY 3D scanning

WRITTEN
BY
**SEAN
RAGAN**

landscape has changed a lot. After two years in production and hundreds of millions of dollars in research, the Kinect sensor itself is an oblong black bar, mounted on a servo-controlled base, with five major sensing components — left and right microphone arrays, an RGB video camera, an IR laser projector, and a monochromatic CMOS image sensor to match the laser. The laser/CMOS pair allows for depth sensing by invisible structured-light scanning.

Generally speaking, Kinect has proven an incredibly fruitful platform for developing all kinds of hacker projects, most of which exploit its native 3D-imaging ability. Between the practical advantages of invisible SLS and Kinect's very low price point, interest in visible-wavelength SLS methods has faded somewhat. Kinect provides a high-performance out-of-the-box 3D scanning system at very little cost, and presents a very attractive alternative to cobbling together a visible SLS system using a digital camera and a video projector. As of this writing, a new Kinect sensor costs about \$100, and the software is widely available for free.

Among 3D scanning programs for Kinect, the frontrunner is ReconstructMe (see page 95) from Austria's Profactor GmbH. ReconstructMe is a commercial software suite that can be freely used for

noncommercial projects. It's available both as a command-line "console" and as an SDK for developing custom apps. ReconstructMe works at a variety of scales and can automatically capture models at their real, measurable sizes, so after-the-fact scaling isn't required. Unfortunately, ReconstructMe is only available for Windows.

Skanect, from France's Manctl, is another popular, free-to-use Kinect-based scanning program that provides support for both Windows and Mac OS X.

IMAGE-BASED MODELING

If you have a good set of all-around photographs of your subject, there are programs that can use those images to reconstruct a 3D representation of the subject. This process is sometimes called *photogrammetric modeling*, and is a fairly advanced application of the same forensic techniques used to reconstruct crime scenes, automobile accidents, and archeological sites based only on 2D photographs. Common reference points are first identified among photographs — either manually or by smart image analysis software — and then located in space by triangulation with the position of the camera.

Programs like Eos Systems' PhotoModeler, D Vision Works' D Sculptor, and Autodesk's

123D Catch (see page 93) provide an interface that makes it easy to mark reference points between photographs, as well as the software back end to actually crunch the numbers and generate the 3D models.

Image-based modeling works best when you have free access to the subject to capture as many pictures as you need ("Print Your Head in 3D," makeprojects.com/project/p/2194). The more images, the better the lighting, and the more consistent the camera positioning between shots, the better the results are likely to be.

For simple, angular shapes with good photo coverage and clear reference points, software can automatically identify and correlate reference points between images, and produce a fairly accurate 3D model, without assistance from a human operator. In practice, some manual identification of reference points between photographs — a process known as *stitching* — is usually necessary. Complex organic shapes, monochrome colors, and matte surfaces all make it harder to identify reference points between images, and subjects with these qualities will be harder to model photogrammetrically.

Sean Michael Ragan is technical editor of MAKE magazine. His work has appeared in *ReadyMade*, *c't - Magazin für Computertechnik*, and *The Wall Street Journal*.



Ultra simple DIY laser-line scanning setup: a laser pointer, a wine glass stem, a neutral background, and a video camera.

Tim Anderson

WHICH ONE SHOULD I USE?

The choice of laser-line, structured-light, or image-based scanning depends largely on your available equipment, the size of the objects you want to scan, and the degree of access you have to move, light, and photograph your subject as needed. There is significant overlap between the working scales for the three methods, but as a rule of thumb, laser-line scanning is the highest resolution method, and best for precisely scanning detailed objects smaller than a human head. Structured-light scanning covers the middle ground between head-sized and room-sized subjects. For large outdoor statues, buildings, and topographical features, image-based modeling may be the only practical method.

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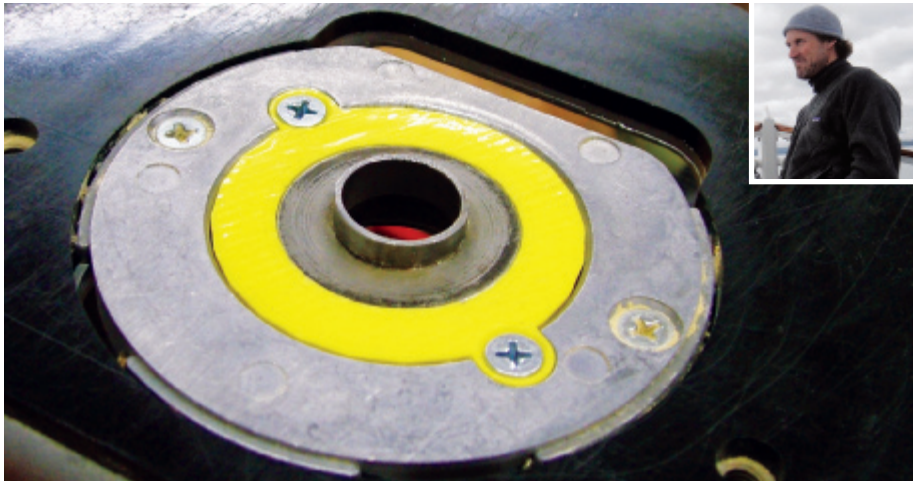
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“My old Bosch 1611 is a killer router, but it’s 20 years old and almost impossible to find parts for. I couldn’t find a stock pattern collar adapter, so I just designed and printed my own.”
—Bozo Cardozo, Ketchum, Idaho

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“I have this trick of making chain mail from soda can tabs. The tabs have to be bent first, and the mail looks best if they’re all bent to exactly the same angle. So I designed and printed a custom jaw insert for an off-the-shelf pair of jeweler’s pliers that bends the tabs exactly the same way each time.”

—Sean Michael Ragan, Austin, Texas

thingiverse.com/thing:31635

“I bought a tackle box to help organize all my electrical components. Unfortunately I didn’t realize until I got home that it was missing a clip, and since it was the last one on the shelf (who sells out of tackle boxes?) I wouldn’t be able to exchange it. I fixed my problem by modeling a replacement from photos of the existing clip and caliper measurements. The replacement actually snaps tighter than the original, so I replaced them both!”

—Chris Krueger, Arlington Heights, Ill.

thingiverse.com/thing:9419



“A friend is a vintage computer junkie and one of his recent purchases was a printer/plotter for his Sharp PC-1500A pocket computer. Although the printer works, the pens, being almost 30 years old, do not. Nor are they still available. So I took out the calipers, busted out OpenSCAD, fired up the MakerBot, and printed one out!”

—Miles Lightwood, Eagle Rock, Calif.

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“When some plastic part breaks in your car, the chances of finding a replacement and then being able to buy it without getting a second mortgage are slim to none. My Thing-O-Matic allowed me to replace a broken plastic fitting in my car’s luggage cover, which saved me from having to buy a whole new one at roughly half the price of my 3D printer kit. I have now helped many others make vacuum cover clips, shower head holders, and many other hard-to-find replacement parts.”

—Miguel Angelo de Oliveira, Hartsdale, N.Y.

thingiverse.com/thing:10043



“A good friend of mine was interested in 3D printing. We were hanging out one Sunday, and he broke the window crank in his Miata. The auto parts store was not open until Monday, so I whipped this up for him using SolidWorks and my MakerBot.”

—Michael Gregg, Palo Alto, Calif.

thingiverse.com/thing:20028



“I wanted to attach a rear light to my bike, but I have a rack installed, so it couldn’t go on the seat post. The rack already had holes for a license plate, so I made this simple adapter that goes on the rack using the existing holes, and then has a spring clip that fits the bike light directly, so that I can attach and remove it quickly.”

—Gian Pablo, San Francisco, Calif.

thingiverse.com/thing:8947



“Some blockhead came along and broke my mother’s doorbell by excessively pounding on it. Not just once, either. Instead of spending money on buying another doorbell button, I decided to make something stronger, better – not sure about the faster part, but you get the idea. I printed it in natural ABS. I can’t even tell a difference from before; it looks exactly the same, but now its stronger – a solid mini-brick instead of a hollow shell. In your face, doorbell murderers!”

—George Banovac, Stony Creek, Ontario

thingiverse.com/thing:10697

“I ordered a KitchenAid stand mixer and its ice cream maker attachment. The ice cream maker attachment arrived on a Monday, but the mixer itself wasn’t going to arrive until the following Thursday. I wanted ice cream on Tuesday. This is my solution: an adapter to drive the ice cream maker with a standard 3/8 drill socket adapter (and a strong drill).”

—Lee Holmes, Seattle, Wash.

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Garrett Finney is the founder of Cricket® Trailer. An architect and designer, he formerly worked on NASA's International Space Station and its "habitation module" (where astronauts eat, sleep, bathe and relax while exploring outer space). With Cricket, Finney has created an innovative twist on the traditional trailer, light enough to be towed by today's small cars. Crickets are compact and flexible homes-away-from-home in which to travel and explore our world here on Earth.

It's no accident that Finney chose to integrate ShopBot into the manufacture of his trailers. Cricket has re-thought the design of the traditional trailer; meanwhile, ShopBot has reinvented CNC fabrication tools to make them usable by anyone with the urge to design and make. "We started designing in 2009 and had immediate consumer interest," says Garrett. "By 2012 we needed to scale production; we turned to ShopBot to help us meet that demand." Cricket uses a full-size ShopBot to cut the aluminum panels that form the core structure of each Cricket.



The Cricket's shell is made from aluminum composite panels cut on a ShopBot. It provides an unprecedented degree of insulation without warping, mold or formaldehyde fumes. The result is a lightweight and athletic trailer that exceeds industry norms for innovation, aerodynamics and durability.

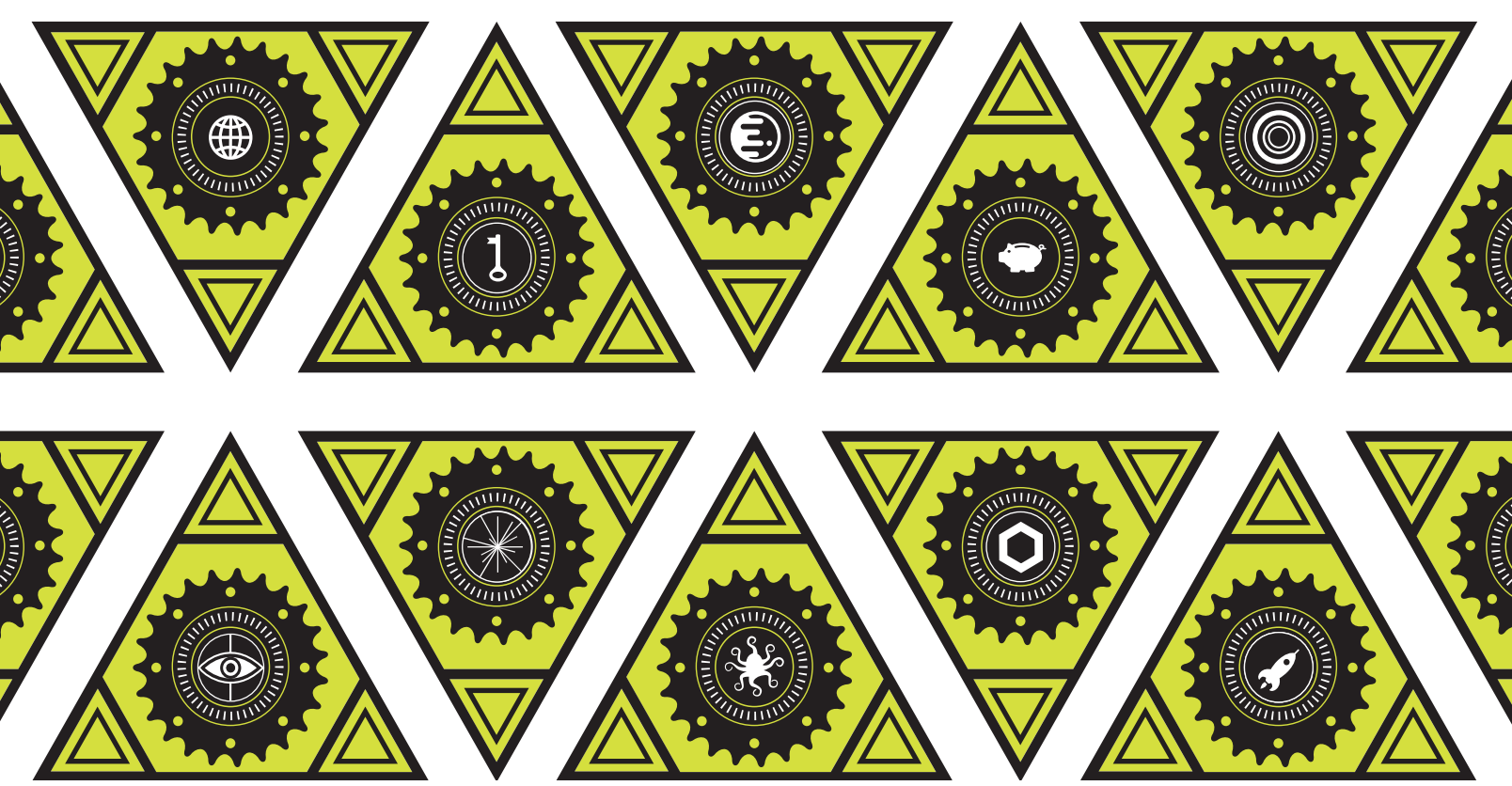
ShopBot commissioned their own Cricket for transporting ShopBot Desktops to Maker Faires around the U.S.; thousands of people attended Maker Faire 2012 in NYC, and learned about the enabling power of digital fabrication tools.

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