

*AIMS-IMAGINARY, Cape Town, 5-7 November 2014*

# Low-cost 3D Printing

*Maths you can touch*

Tarig Mahgoub Hassan Abdelgadir,  
Marco Rainone, Enrique Canessa, Carlo Fonda

<http://scifablab.ictp.it>



The Abdus Salam  
**International Centre  
for Theoretical Physics**

50th Anniversary 1964-2014



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About the ICTP





About the ICTP



Founded in 1964, the Abdus Salam International Centre for Theoretical Physics (ICTP) operates under a tripartite agreement between the Italian government, the International Atomic Energy Agency (IAEA), and the United Nations Educational, Scientific and Cultural Organization (UNESCO).



ICTP Photo Archives

Participants in the 1960 seminar that spurs the creation of ICTP. Abdus Salam, who was teaching at Imperial College in London, is on the right. Paolo Budinich, the chief organizer of the seminar, is to his immediate right.

the chief organizer of the seminar, is to his immediate right. who was teaching at Imperial College in London, is on the right. Paolo Budinich, participants in the 1960 seminar that spurs the creation of ICTP. Abdus Salam, ICTP Photo Archives

MIRAMARE CASTLE, TRIESTE  
22-26 JUNE 1960  
SYMPOSIUM ON ELEMENTARY PARTICLE INTERACTIONS



**IAEA**

International Atomic Energy Agency

International Atomic Energy Agency

**IAEA**



The background of the slide features three flags flying on tall poles in front of a modern building with many windows. From top to bottom, the flags are the Italian national flag (green, white, and red vertical stripes), the United Nations flag (light blue with a white world map and olive branches), and the ICTP flag (red with a white stylized 'I' and 'C' logo).

# ICTP mission is to:

Foster the growth of advanced studies and research in physical and mathematical sciences, especially in support of excellence in developing countries.

Develop high-level scientific programmes keeping in mind the needs of developing countries, and provide an international forum of scientific contact for scientists from all countries.

Conduct research at the highest international standards and maintain a conducive environment of scientific inquiry for the entire ICTP community.



# Stats: activities

ICTP hosts every year:

- >6000 scientists
- >50 scientific activities  
(international conferences)

For a total of 150.000+ visitors  
from 1964 to 2014



- 60% from Developing Countries
- 40% from Developed Countries





# Agenda of this Workshop

30'

30'

120'

30'

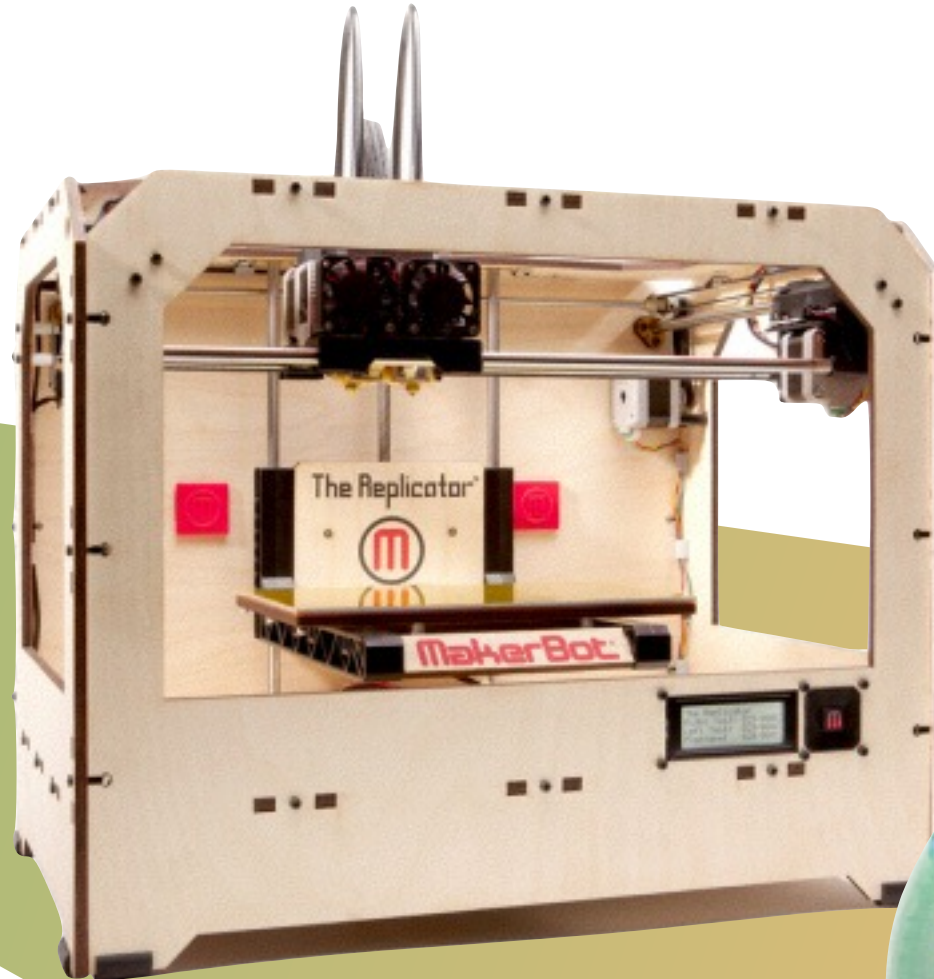
30'

- *Demo*: how to generate 3D objects with OpenSCAD language
- *Demo*: other tools: webapps, K3DSurf, Mathematica™
- Introduction to low-cost 3D printing: how-to & *demo*
- Case studies:
  - replicating IMAGINARY models using low-cost 3D printers
  - getting math objects from *Thingiverse* and other websites
- Discussion



# Intro to low-cost 3D printers

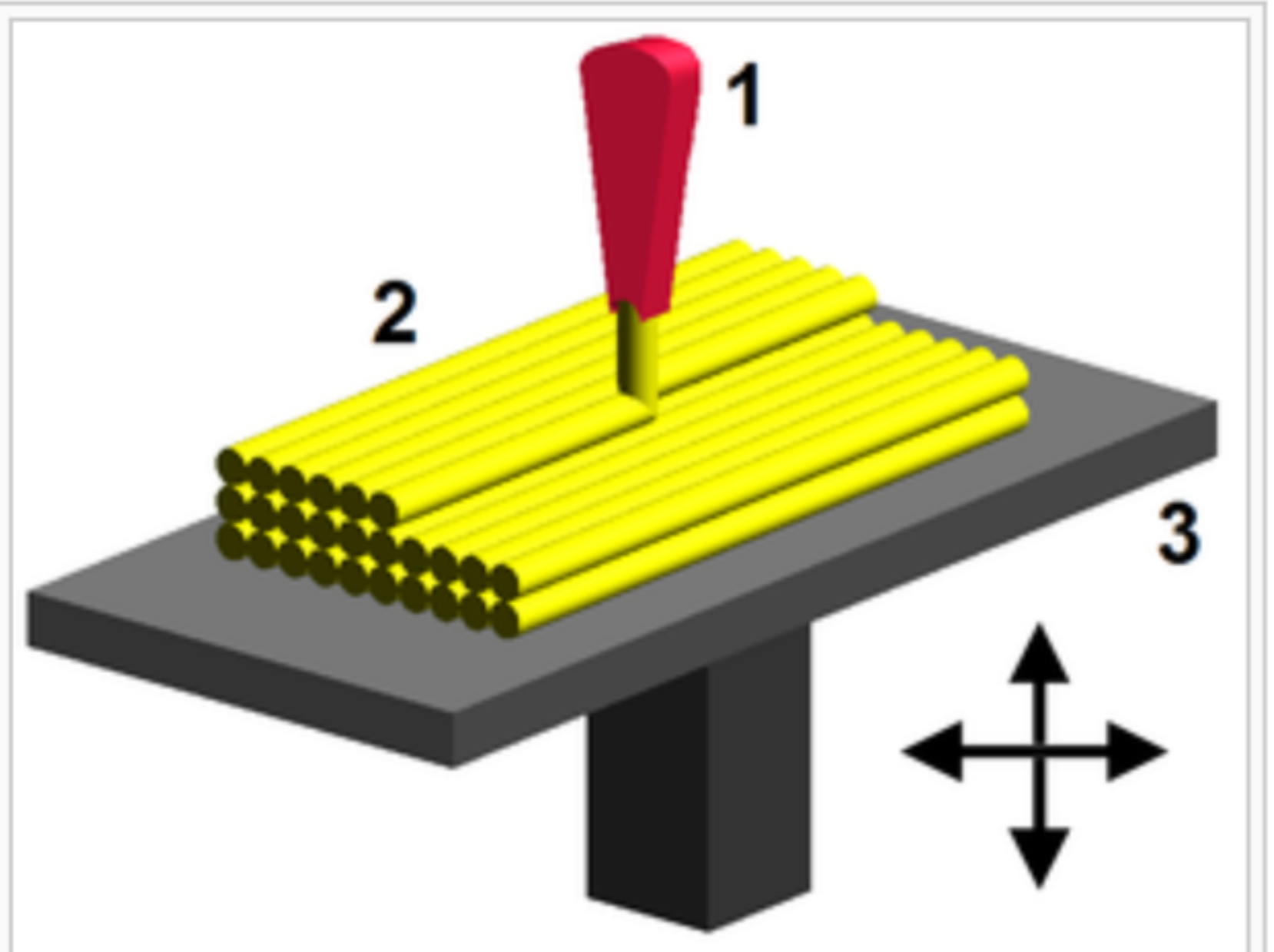
*from printing (on paper) texts and pictures  
to “printing” three-dimensional objects*





# Fused Deposition Modeling (FDM)

- Many technologies are possible for 3D printing.
- The most common one uses molten (liquid) plastic extruded through a nozzle. The nozzle or the object (or more often both) are moved along the three axes X, Y, Z.
- 3D printing is an "additive manufacturing" technique, opposed to the older "subtractive manufacturing" machining systems like milling machines, CNC, etc.



Fused deposition modeling: 1 - nozzle ejecting molten plastic, 2 - deposited material (modeled part), 3 - controlled movable table



# Professional 3D printers (10.000\$+)

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- Pro 3D-printers can print objects
  - in plastic, starting from a filament (with FDM), or
  - in other material (like metals, ceramics, etc.) provided as powder and “assembled” by sintering (SLS)
  - and some are even able to print in full RGB color
- Up to a (very) big size
- Very expensive (“*pro*” market)
- Beautiful results ;-)







Low-cost *personal*  
3D printers

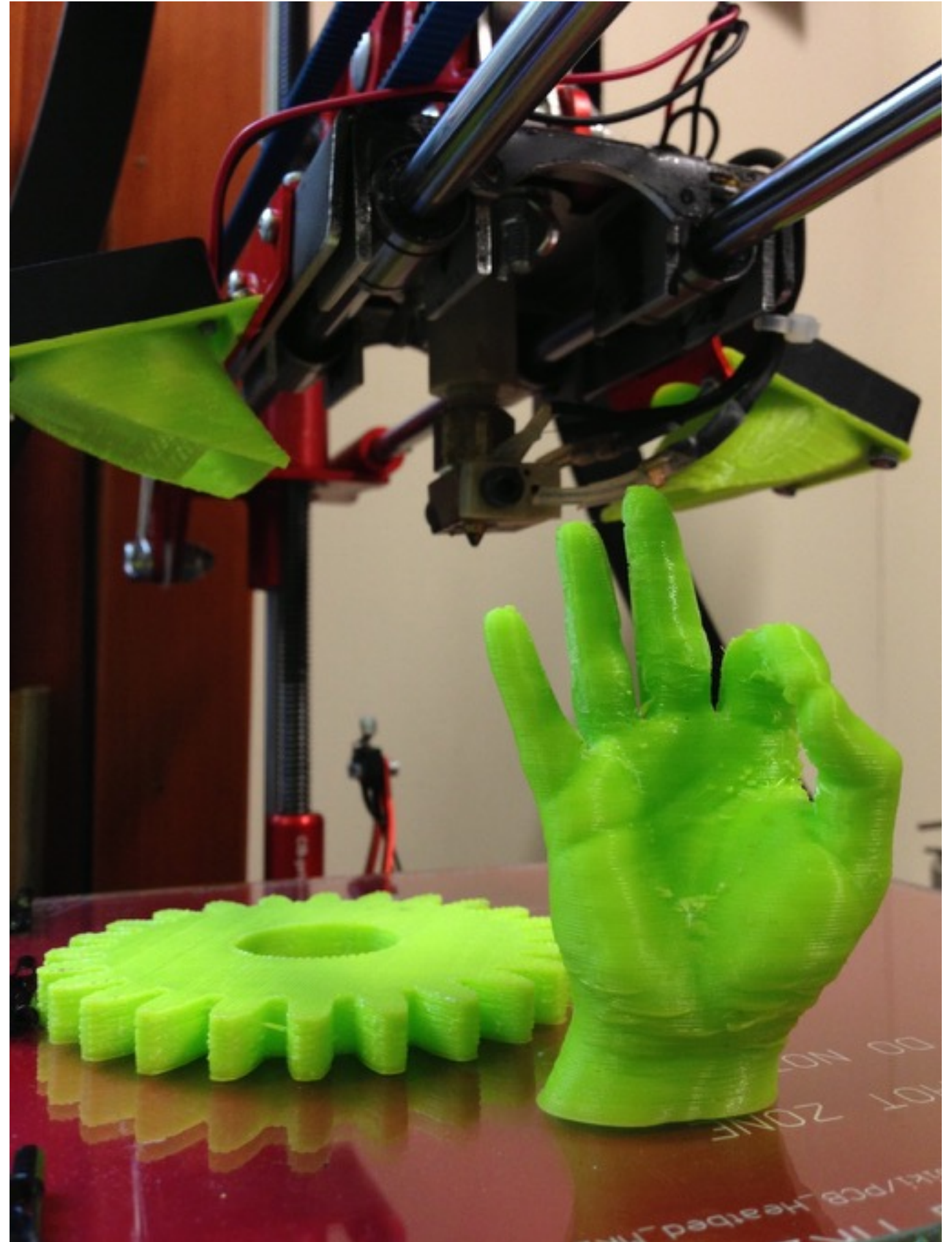
cost: from 300 to 3000 USD



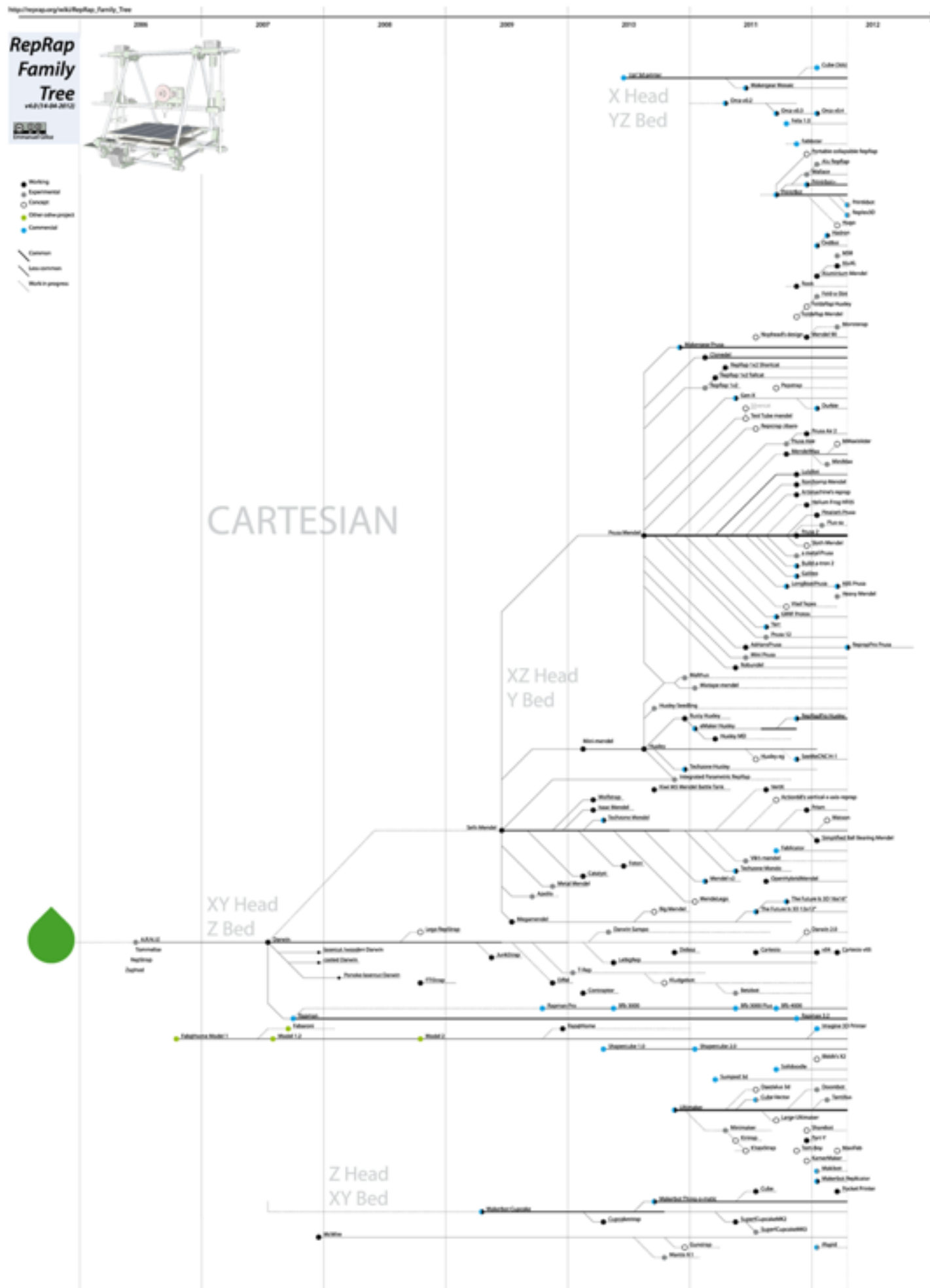
# Open source + Open Hardware

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- Low-cost printers use a plastic filament (ABS or PLA, 1.75 or 3mm thickness)
- usually hand-build, plywood or acrylic frame and parts
- the software is free and open source: 3D design apps, *slicers*, printer control apps, etc
- extensive use of open hardware (Arduino, Sanguinololu, etc. ...small cheap computer boards), blueprints are open and downloadable
- some printers can (partially) **replicate** themselves, because are made with printed parts







0:08

## DIY 3D Printing Mechanics



- Building things with a hot-melt glue gun
- A very **small** glue gun: nozzle 0.2 to 0.6 mm dia
- A very **hot** glue gun: 190 to 230 °C = 350 to 450 °F

<http://www.thingiverse.com/thing:2064>

6

1:08

## Cartesian Coordinates

- Z Axis
  - +Up -Down
- X Axis
  - +Right -Left
- Y Axis
  - +Back -Front
- A Axis
  - Filament drive!



<http://www.thingiverse.com/thing:2064>

7

6:08

## 3D Printing Mechanics

- Z Axis stage
  - Filament drive = A Axis
  - Extruder "Hot End"
  - Nozzle
- X and Y Axis Stages
  - Heated build plate(s)
  - Automated belt (?)
- Build Chamber
  - LED strip lighting!



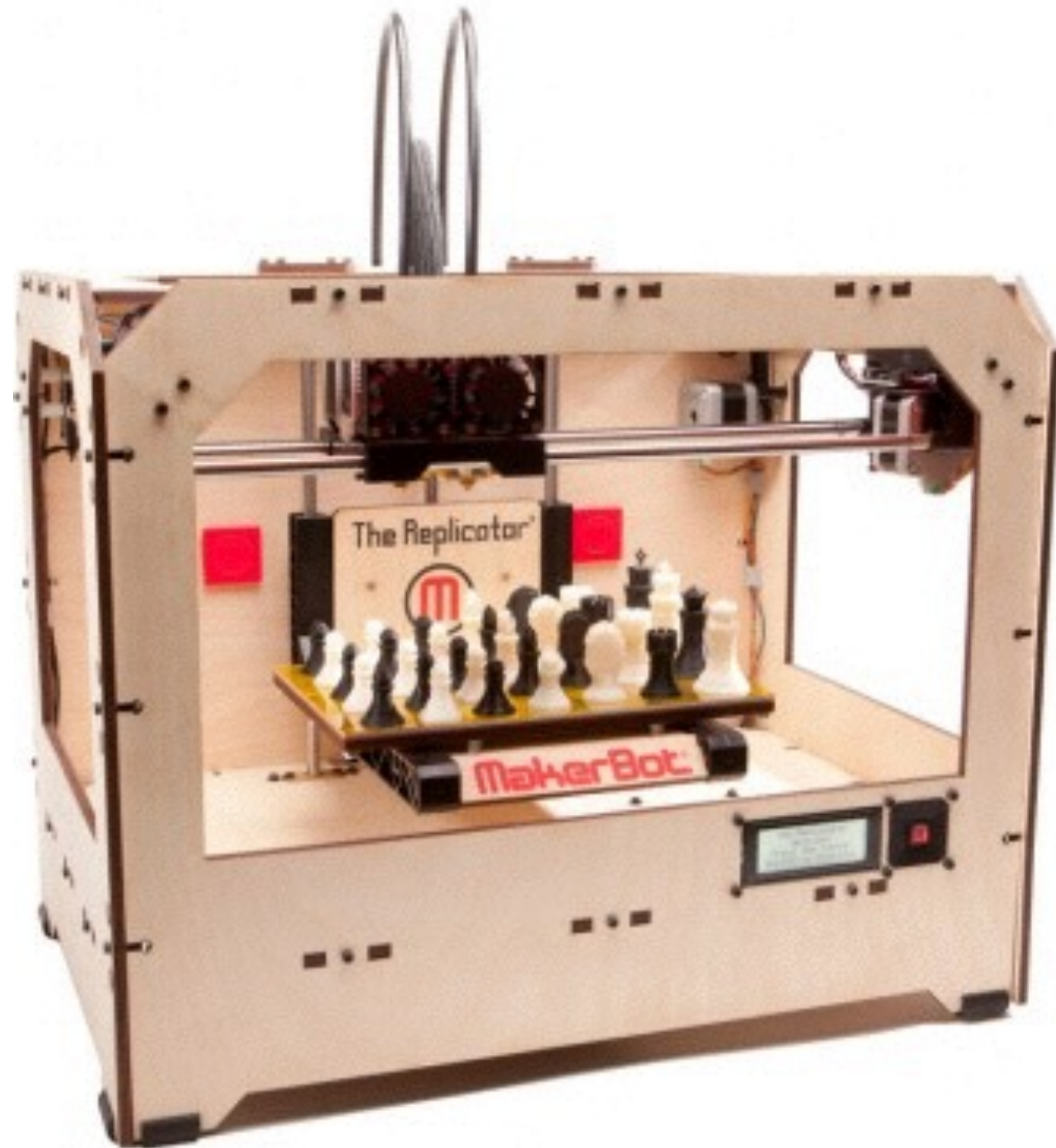
8



# Makerbot Replicator

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- Third generation printer (the first two were the *Cupcake* and the *Thing-o-Matic*)
- Single or *Dual head* (can print in two colors, or two plastic types)

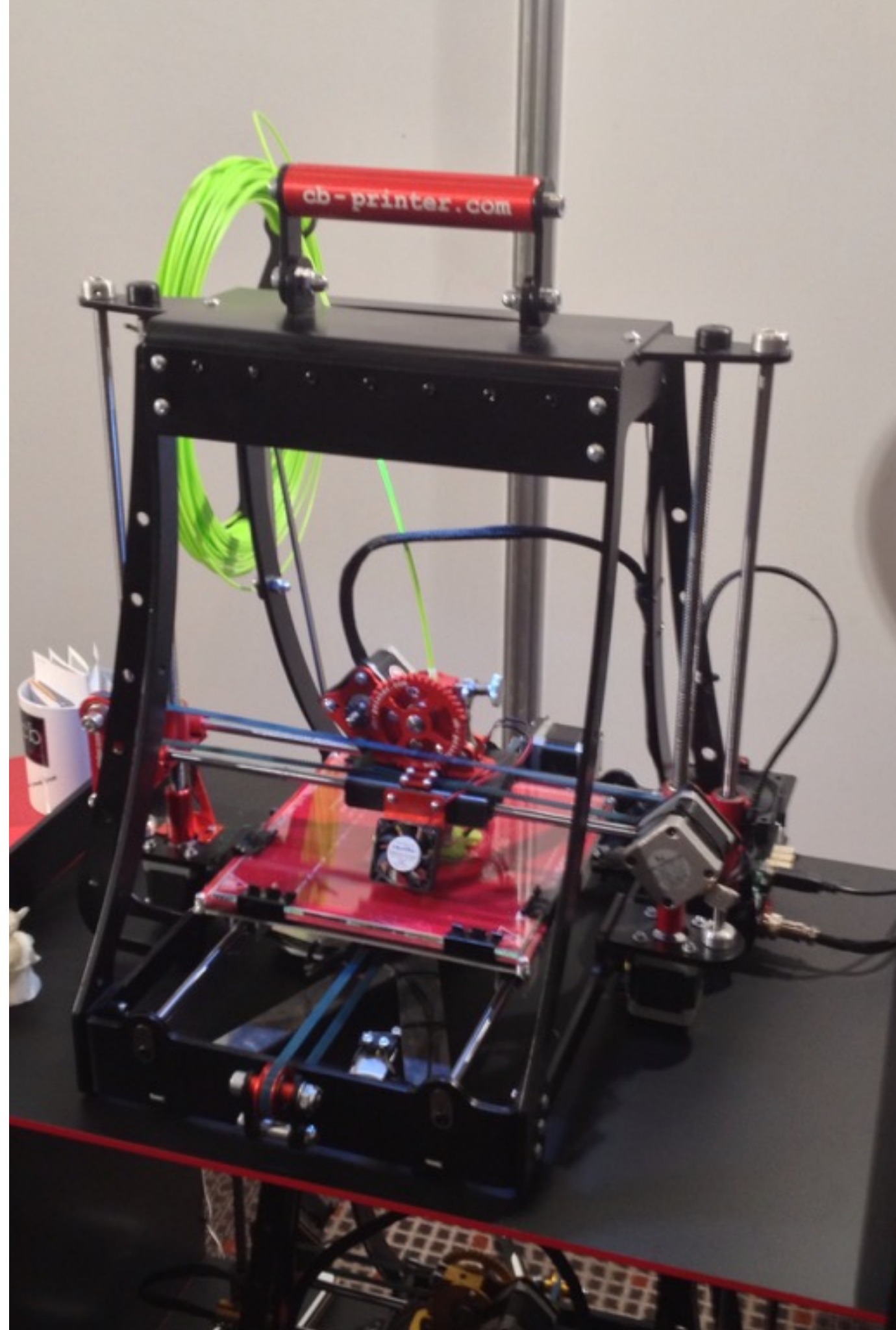




# RepRap: Prusa/ Mendel/Darwin/etc...

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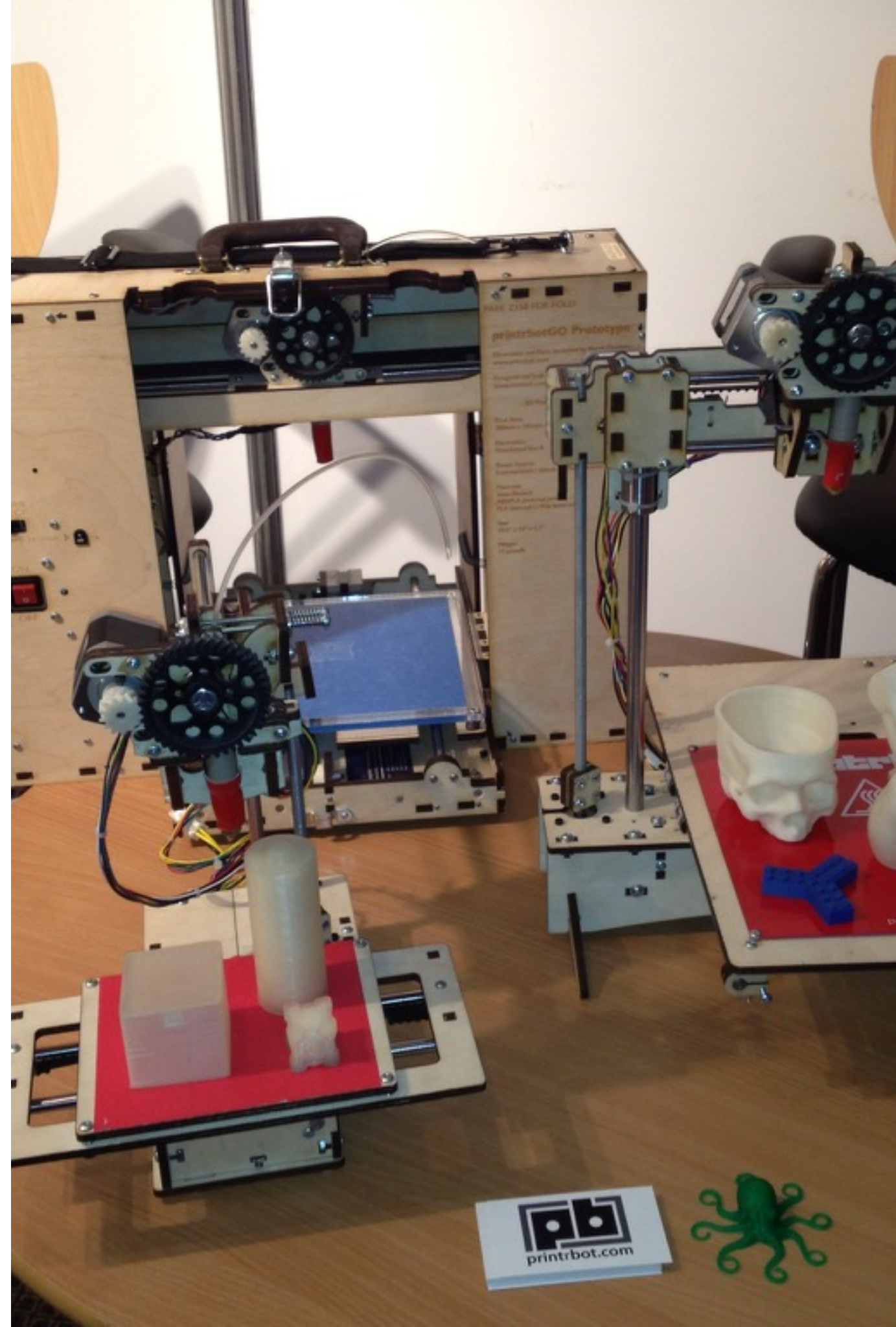
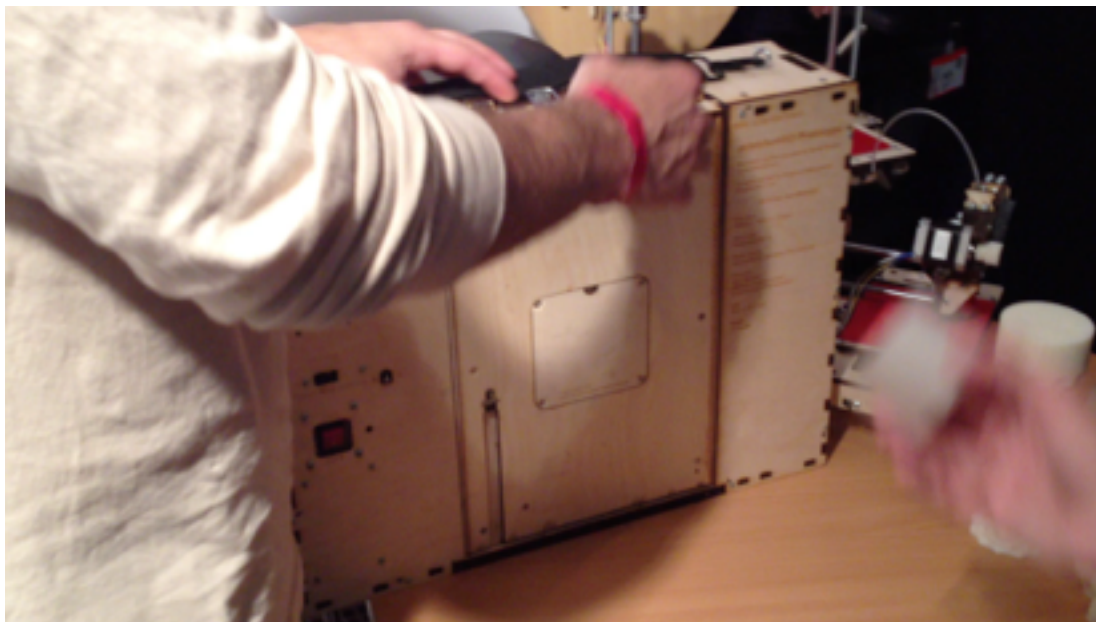
- Many variations on the theme
- Mostly designed (and marketed) by members of the hacker community in US and Europe
- Everything is open, you can buy or build/modify them





# Printrbot

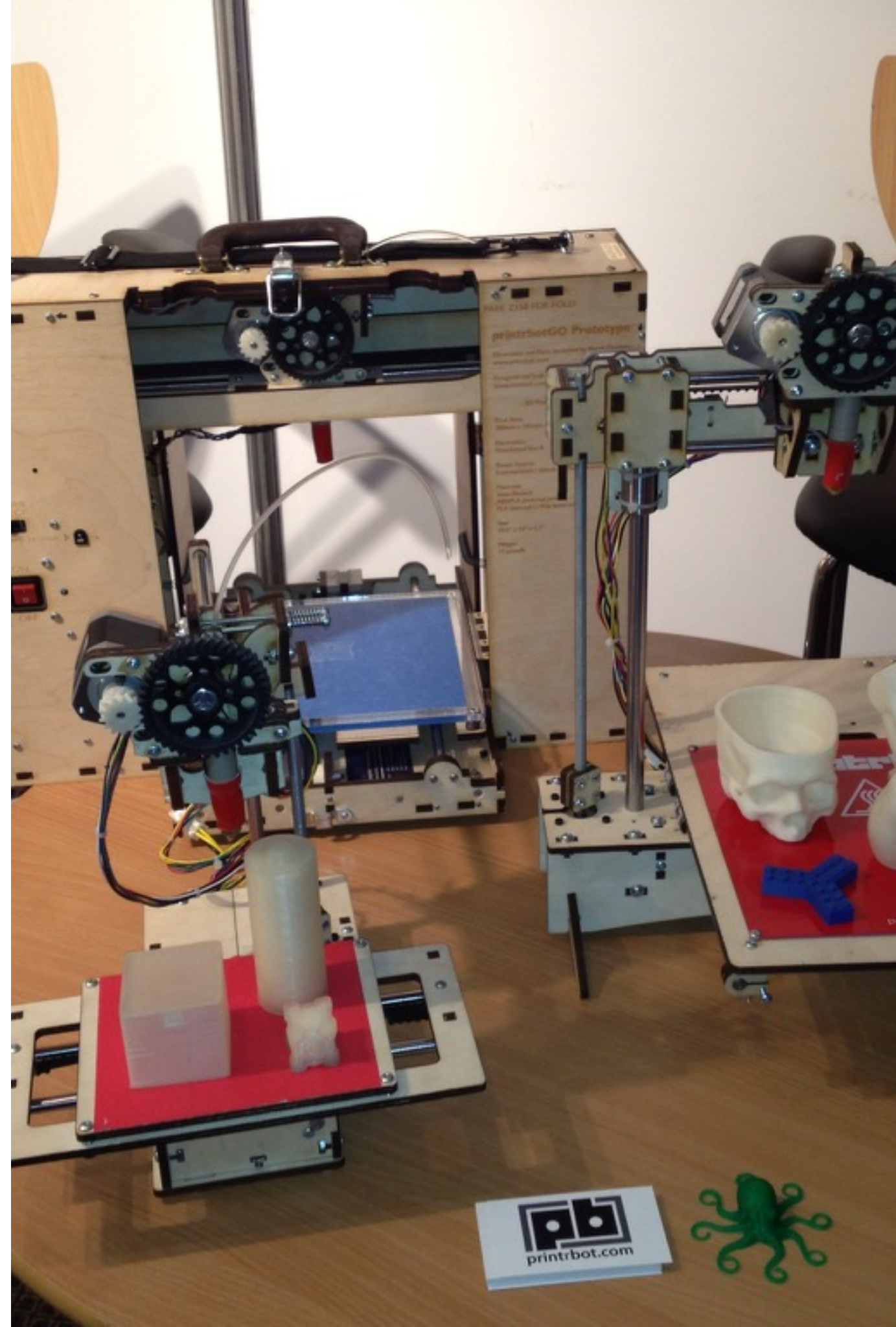
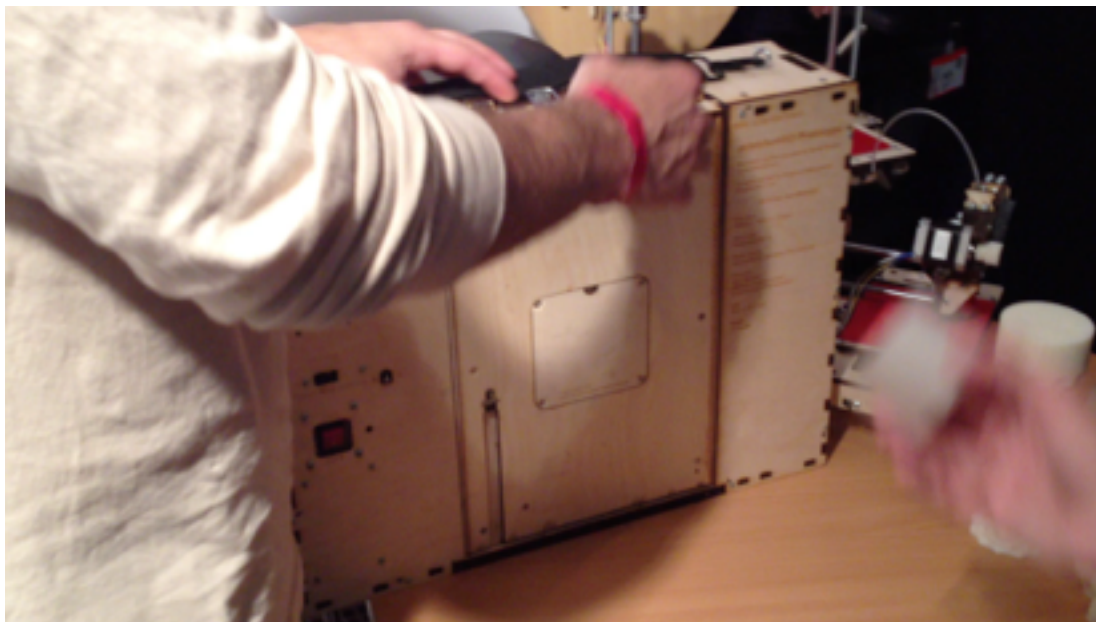
- These are *very portable* models, even battery powered. Mostly designed for education (school), available from the U.S. Cost: starting from ~400\$





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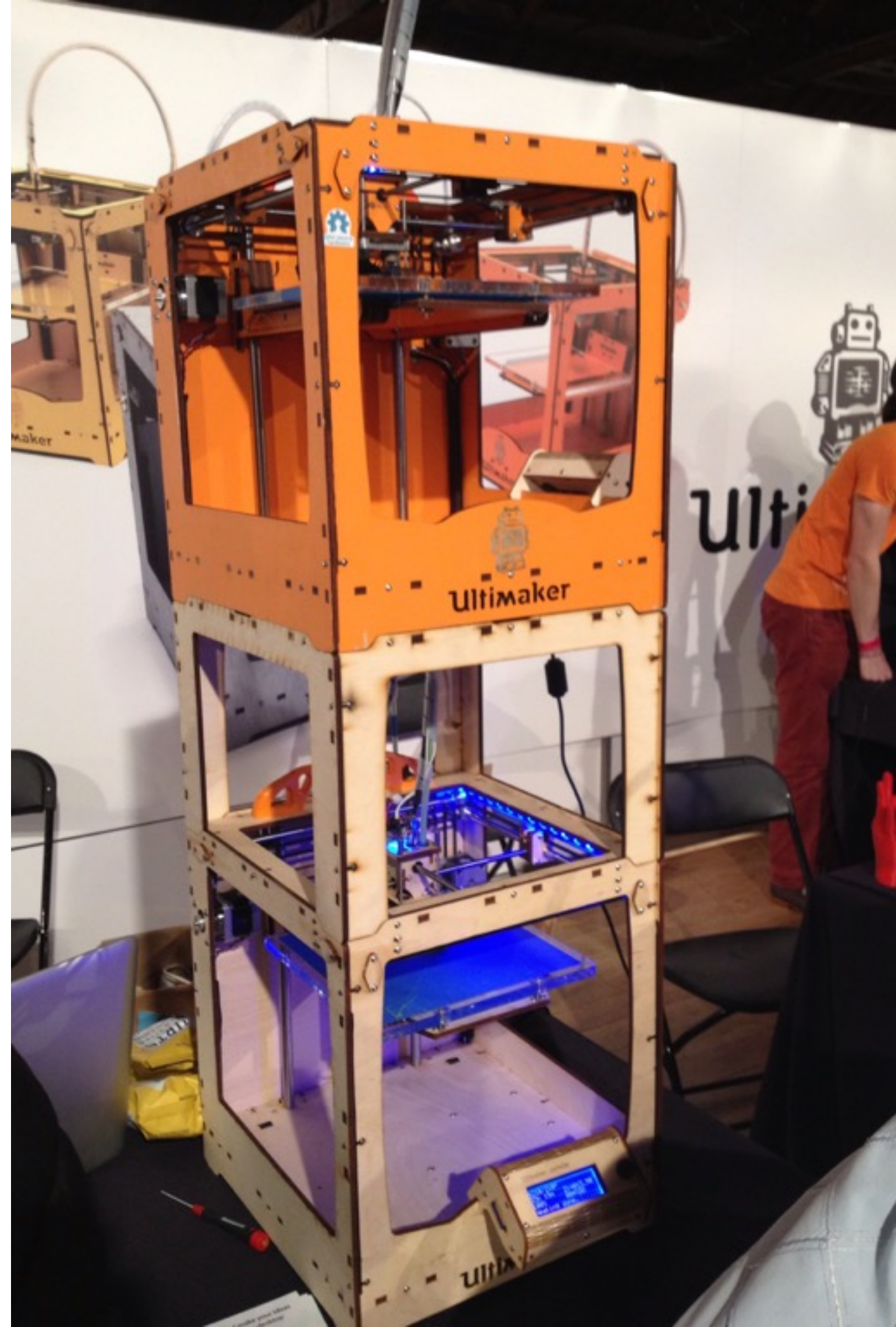




# Not only from U.S.: the Ultimaker

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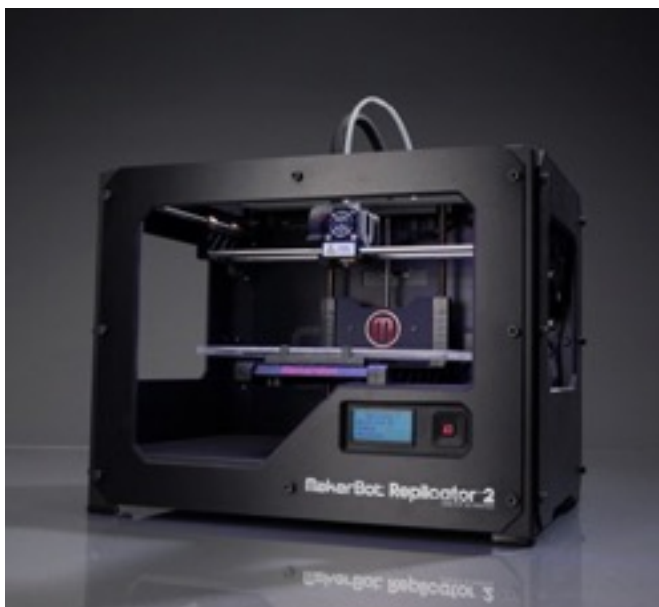
- Developed in the *Netherlands* by a student (as a byproduct of his MSc thesis)
- Cost: €1000 as kit, fully open source





# The Cube

- First cheap commercial "not-for-hackers" plug'n'play printer
- For children, families, etc.
- Also MakerBot's Replicator 2 is going on this track (less "open", but for a much larger market)



The screenshot shows the Cubify website's homepage. At the top is the Cubify logo and a navigation bar with links: Create, Shop, Collections, Cube 3D Printer, Blog, My Cubify, and a search bar. A shopping cart icon shows "My Cart (0)". The main banner features a 3D printer with a yellow filament and a collection of colorful 3D printed objects like a house, a robot, a phone case, and a dinosaur. The text reads: "Cube® A 3D Printer for you. Express yourself in 3D. Easy to use. Only \$1299. Order now." Below this is a section titled "What you can do with your Cube" with three columns: "Get Print Files Online" (with a yellow robot and a green ring), "Customize Online with Free Apps" (with a hand holding colorful blocks), and "Create Anything" (with a computer screen showing a 3D model). Each column has a "Shop now", "Try it now", or "Learn more" button. The "Features" section at the bottom has three columns: "Plug and Play Simplicity" (with a small printer icon), "Print in Vibrant Colors" (with a stack of colorful discs), and "25 Free Creations" (with a collection of colorful 3D models). Each feature column has a "Learn more" button. At the top right of the Features section are buttons for "Activate my Cube", "Download Cubify Client Software", and "Tech Specs".



# The Cube (\$1299)

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# The Cube (\$1299)

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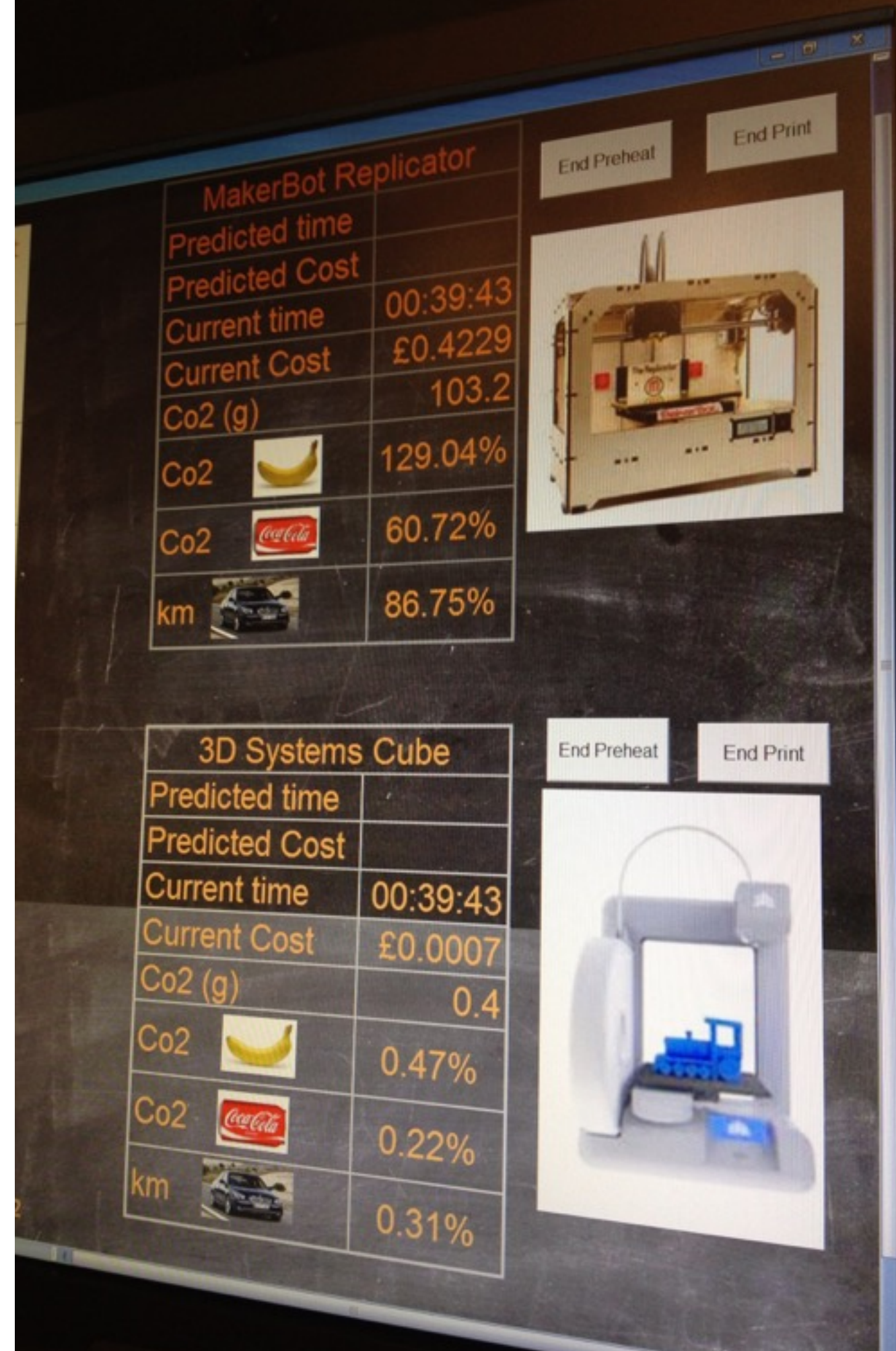




# And many more...

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- Different solutions
- Different level of skills required to operate
- Different prices
- Different philosophies
- The market is still growing quickly and searching an equilibrium...

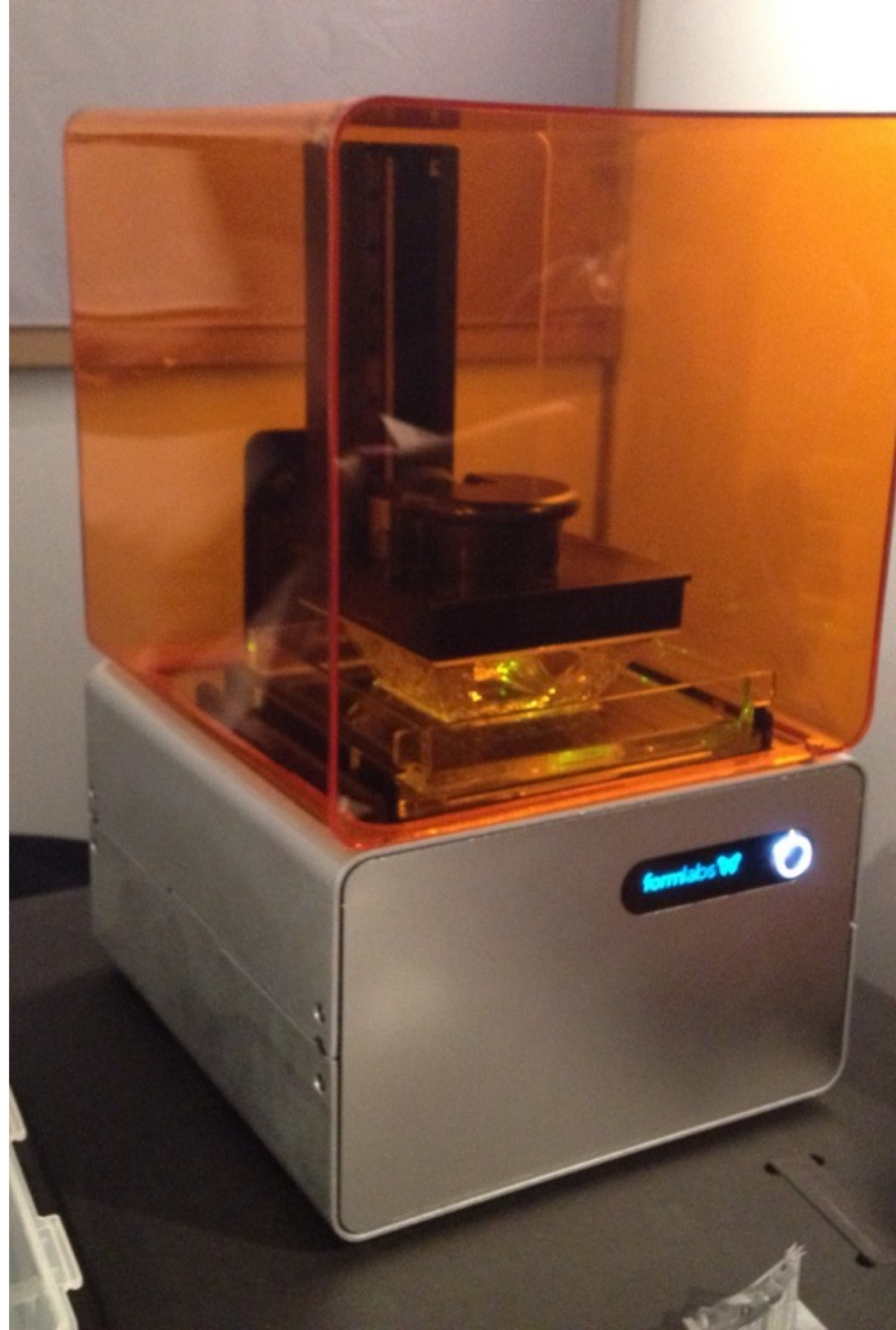
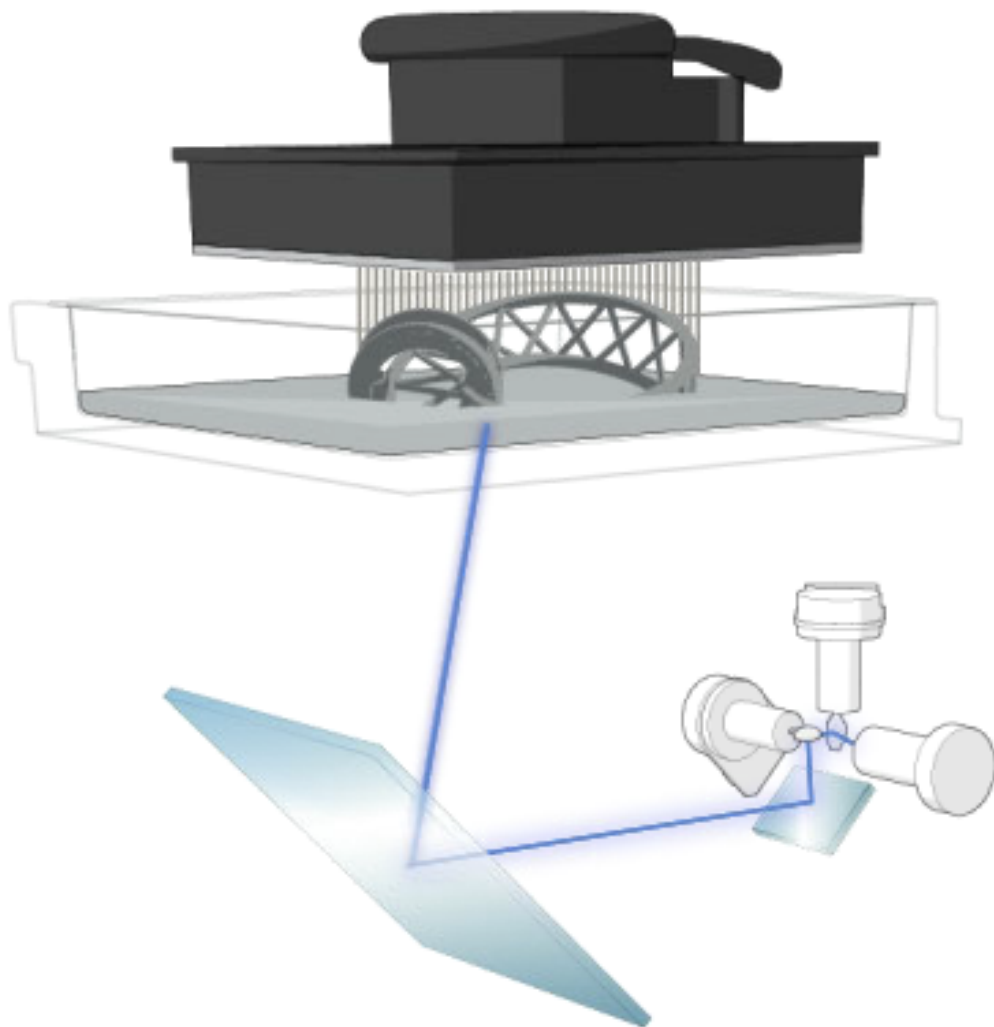




# Laser + liquid resin

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- another promising technology from low-cost 3D printers: it uses a special liquid resin that costs 3x more than plastic, has better resolution and precision.





# History of the Personal Computer (is it repeating all again?)

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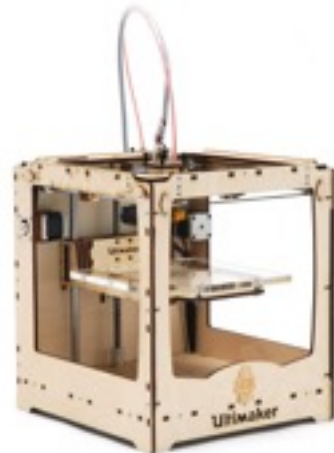
Pro only



first personal  
(for hackers)



really personal  
(mass produced)



?

???





HOW to print an object?

...practical 3D-printing for beginners





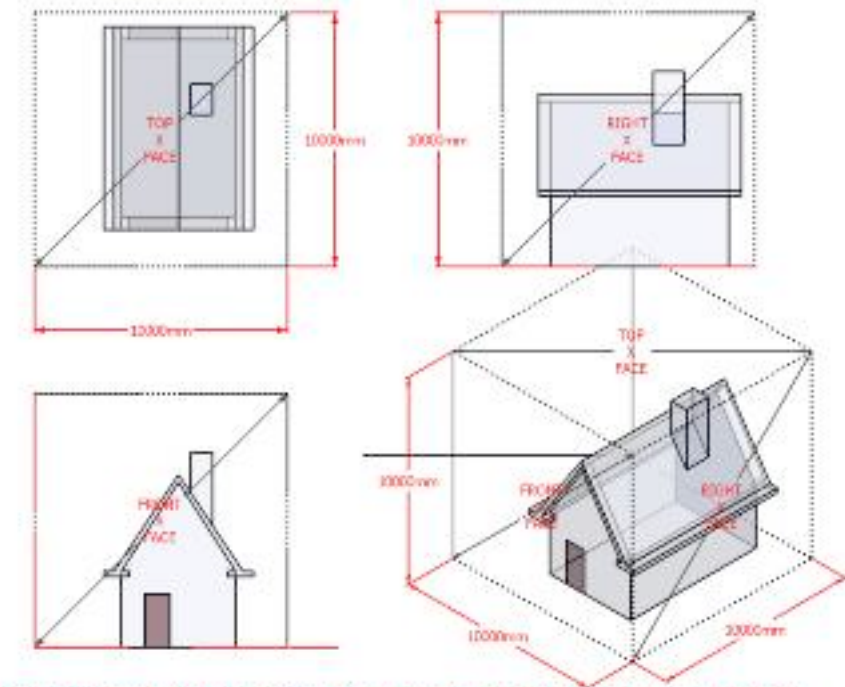
HOW to print an object?

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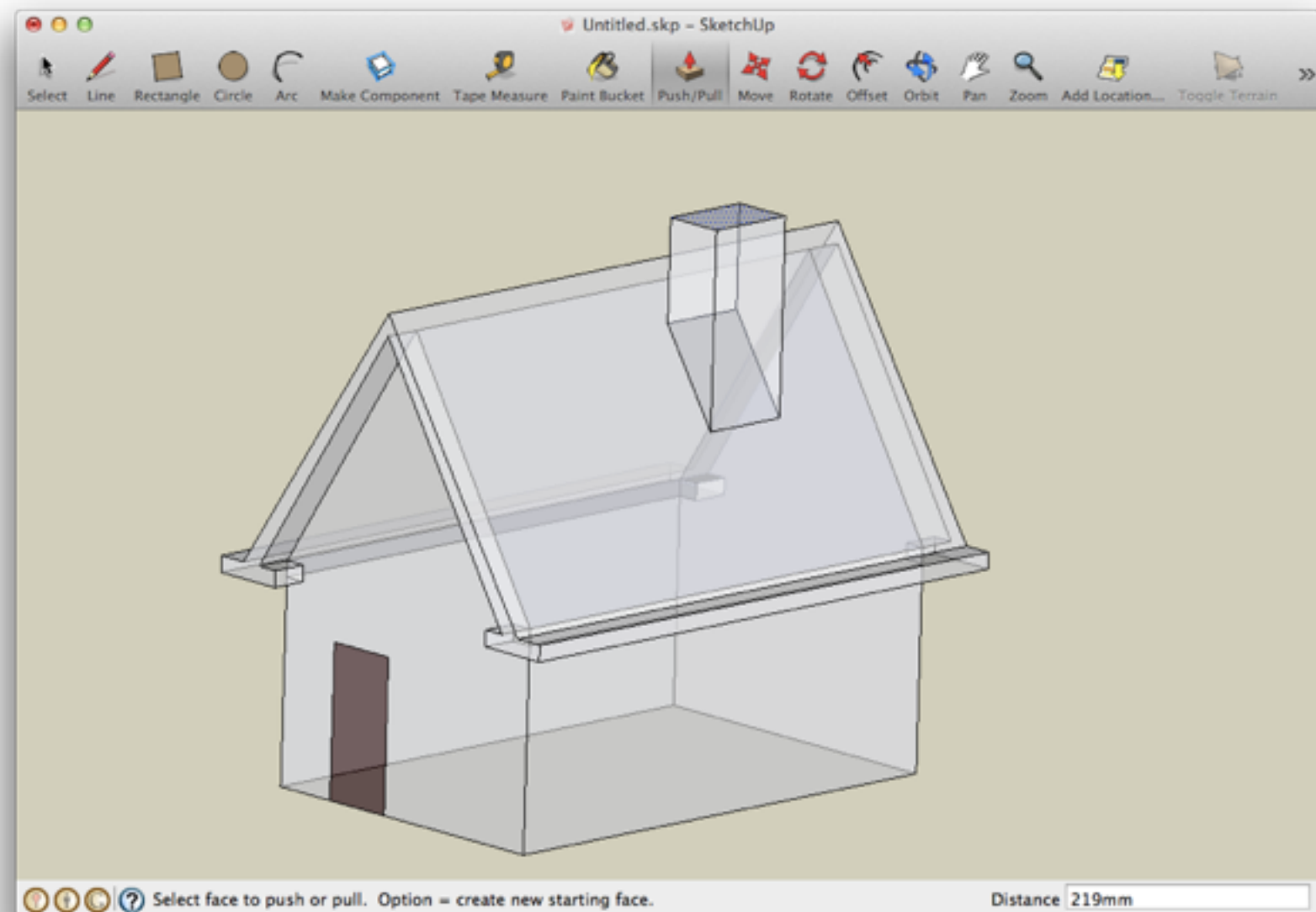


# #1 - Design a model

- The first step for creating a 3D-printed object is to make a digital model of it.
- There are many CAD programs (Computer-aided Design software), some are even free and open source.
- To learn how to use well a CAD program is not easy, it may require some days (or months) and a lot of patience and practice...



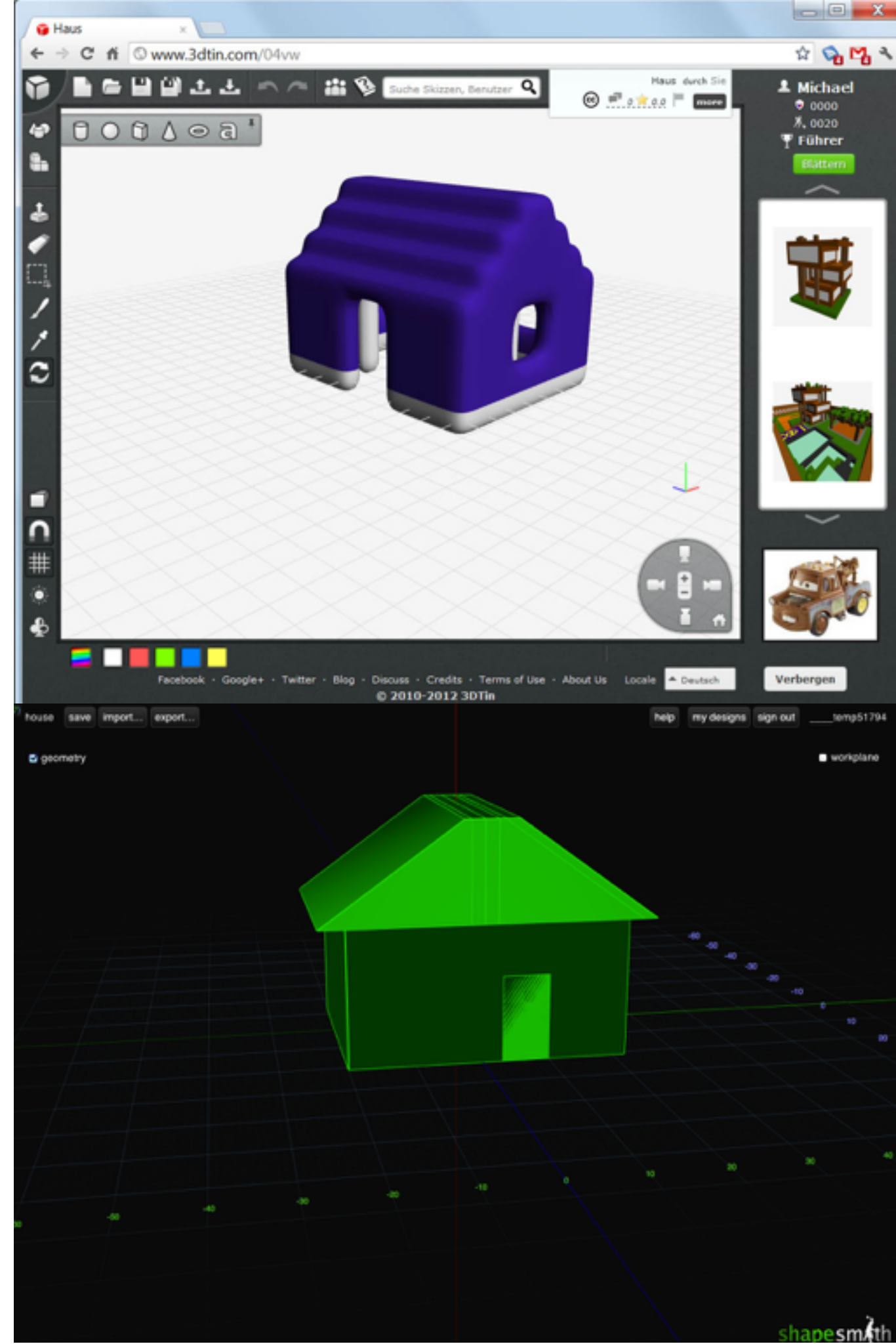
Always work within editing context of the component boundaries. Standard\_Box to update all views (=scene 4) (dashed lines and red measures are just for informative reasons and may be deleted from the component)





# Program VS WebApp




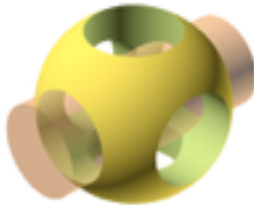
- Sometimes, for a simple model, is easier and quicker to use one of the specialized websites that provide visual tools for an easy and immediate creation and/or modification of your 3D models (these are called **webapps**).
- Examples (*more will follow later, with a short demo*):
  - TinkerCAD
  - 3Dtin
  - ShapeSmith
  - Cubify





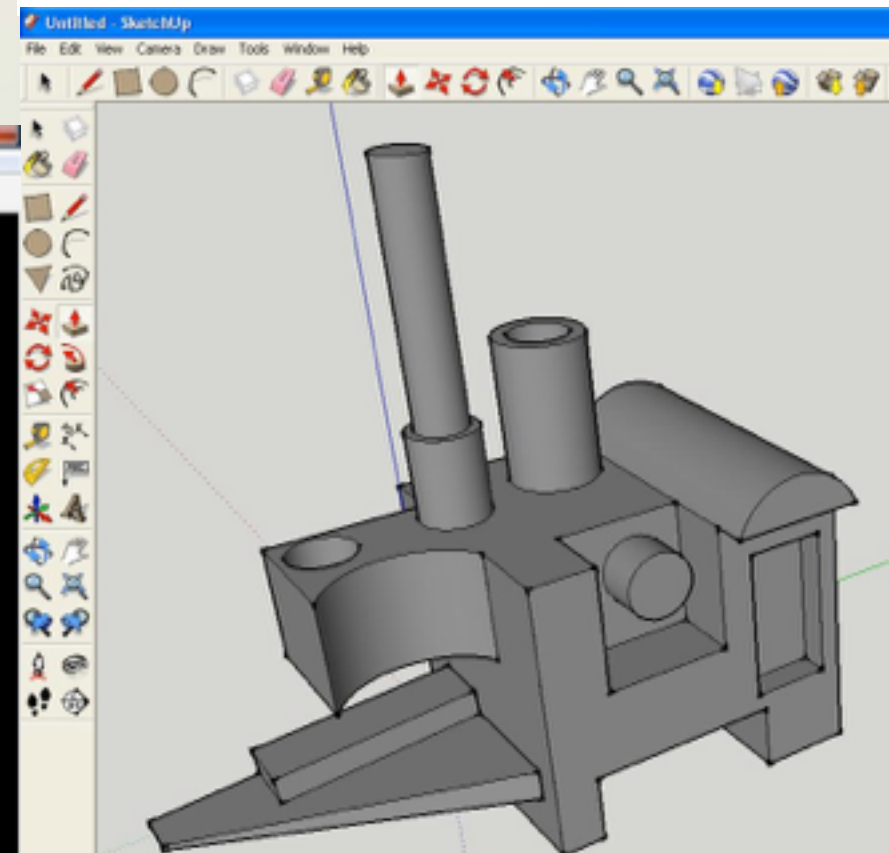
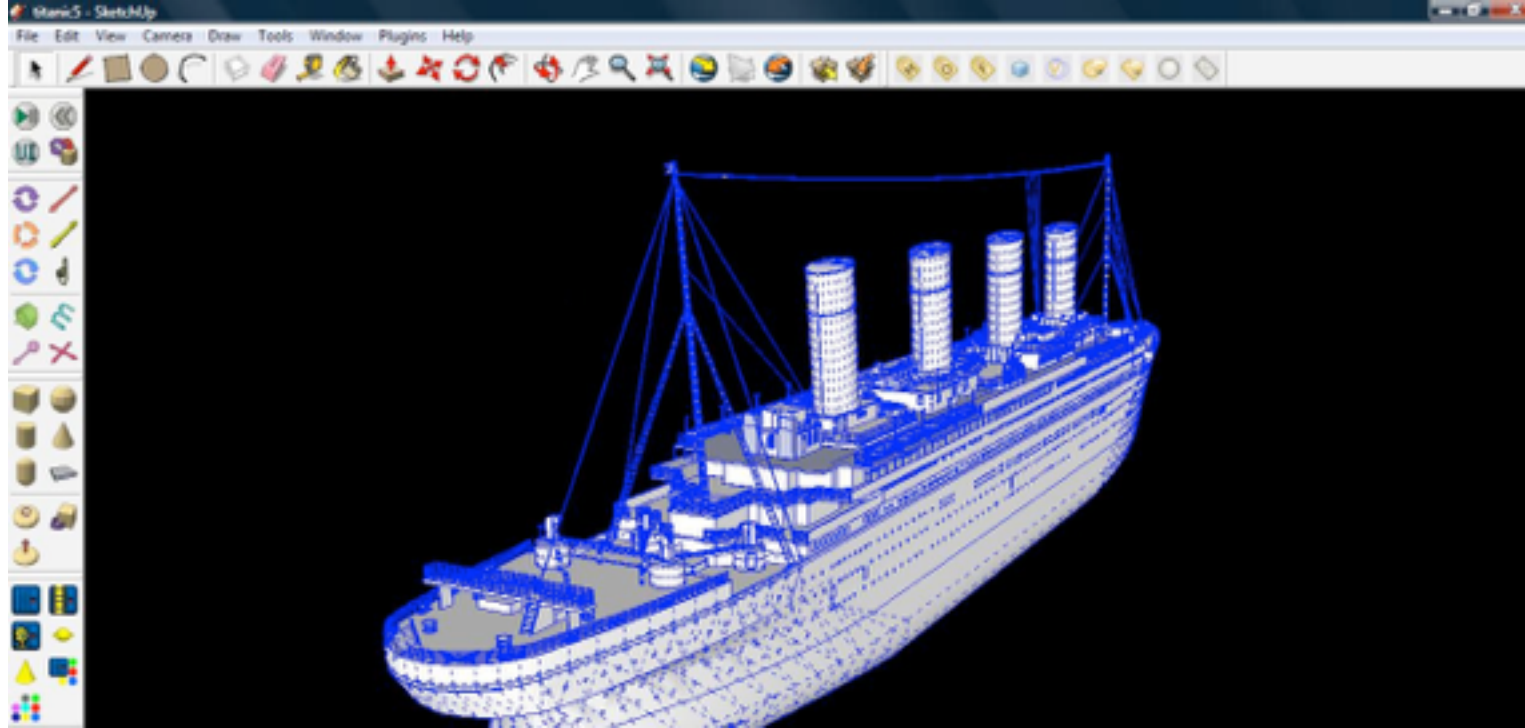
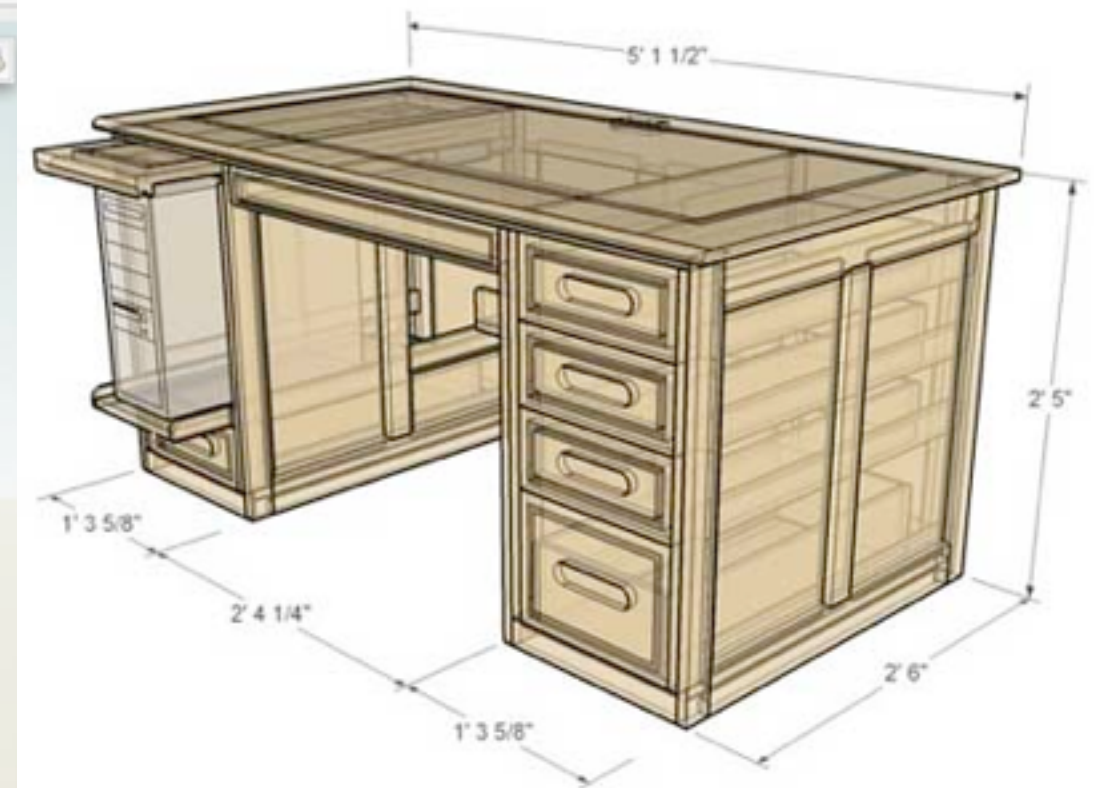
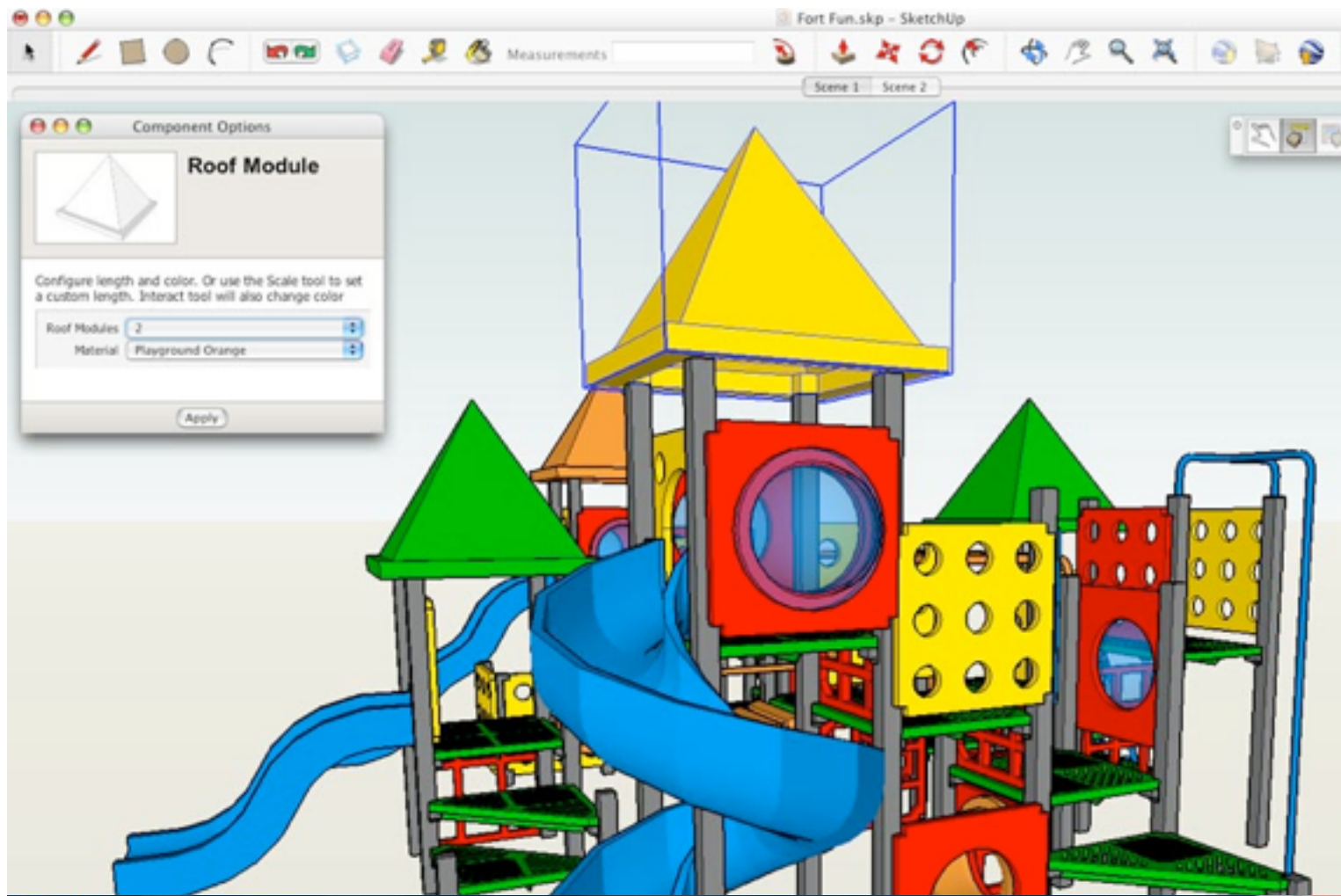
# Examples: *free* software for *technical* 3D modeling

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- SketchUp (by Trimble, *was:* by Google) 
- FreeCAD (open source, Win/Mac/Linux) 
- Blender (open source, Win/Mac/Linux) 
- **OpenSCAD** (programming language) 
- and many others...



# SketchUp: <http://www.sketchup.com>





# Examples: *free* software for *artistic* 3D modeling

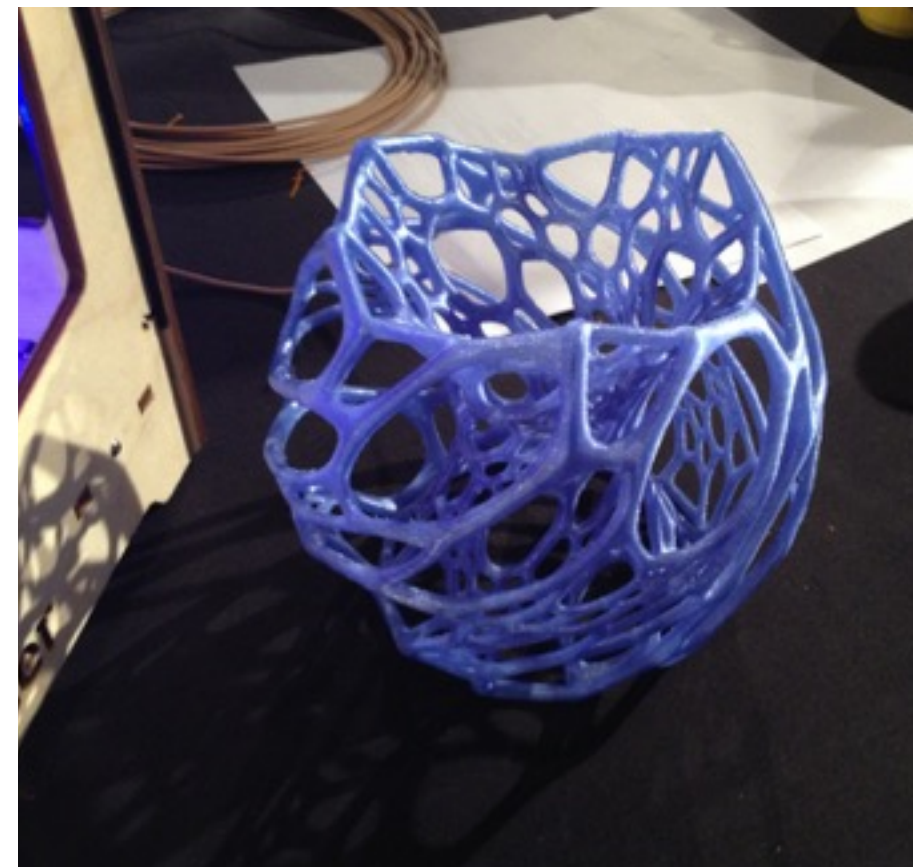
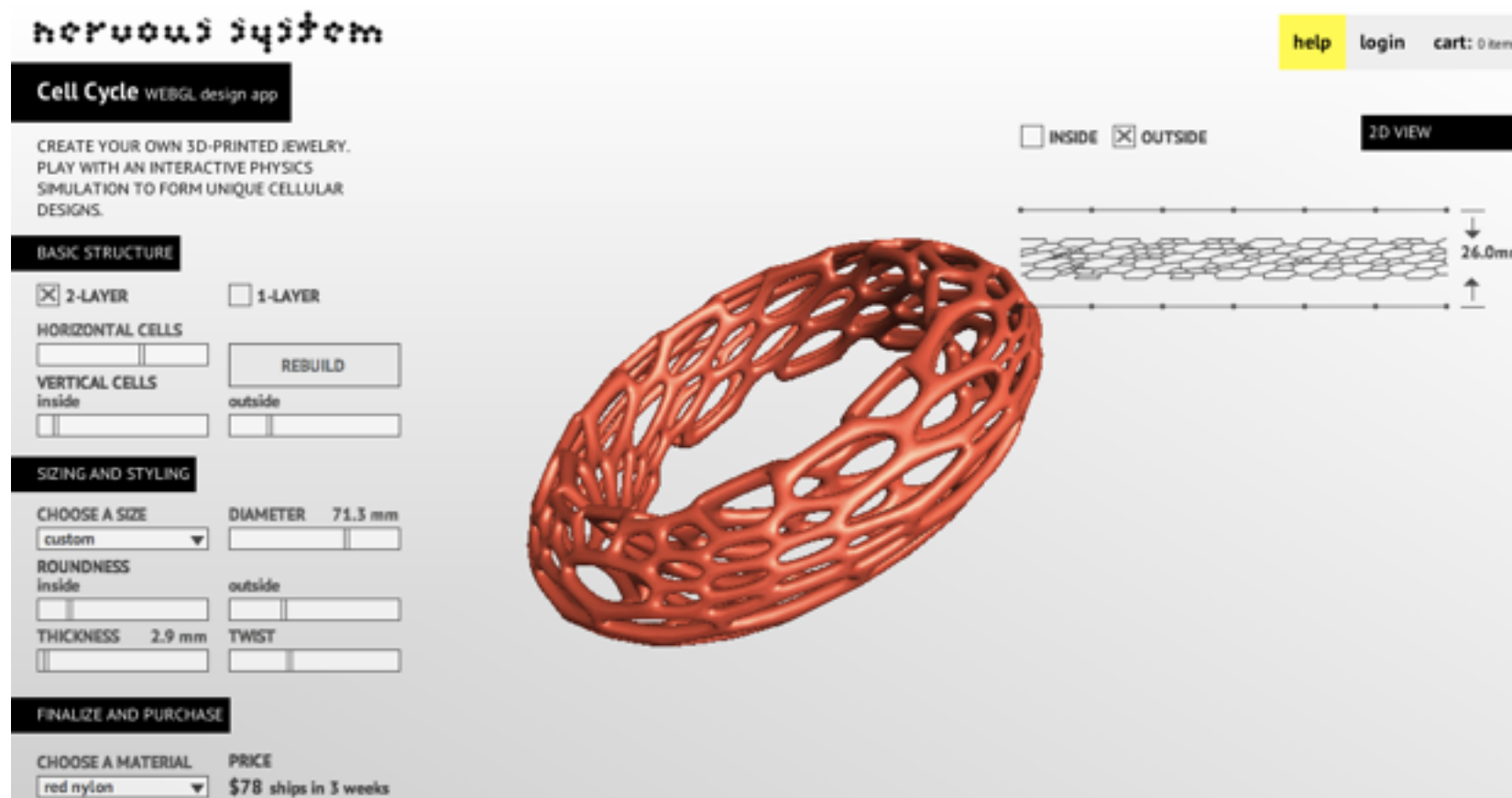
- Sculptris (Win, Mac)



- Autodesk 123D Design (Mac, Win, iPad, web)



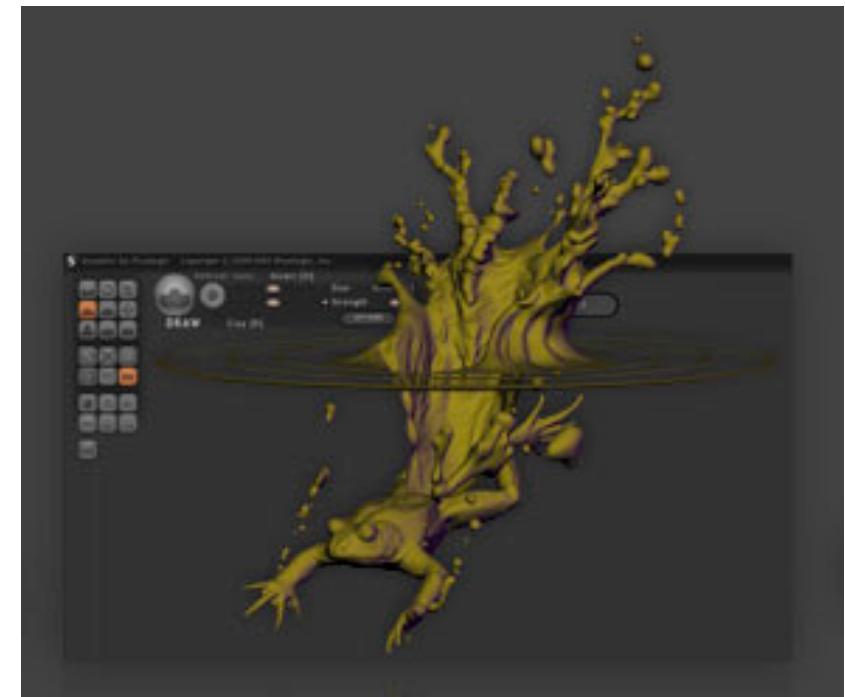
- and a few beautiful webapps (e.g. Nervous System)





**Sculptris:** <http://pixologic.com/sculptris/>

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# File format: STL (StereoLithography)

An ASCII STL file begins with the line:

```
solid name
```

where *name* is an optional string. The file continues with any number of triangles, each represented as follows:

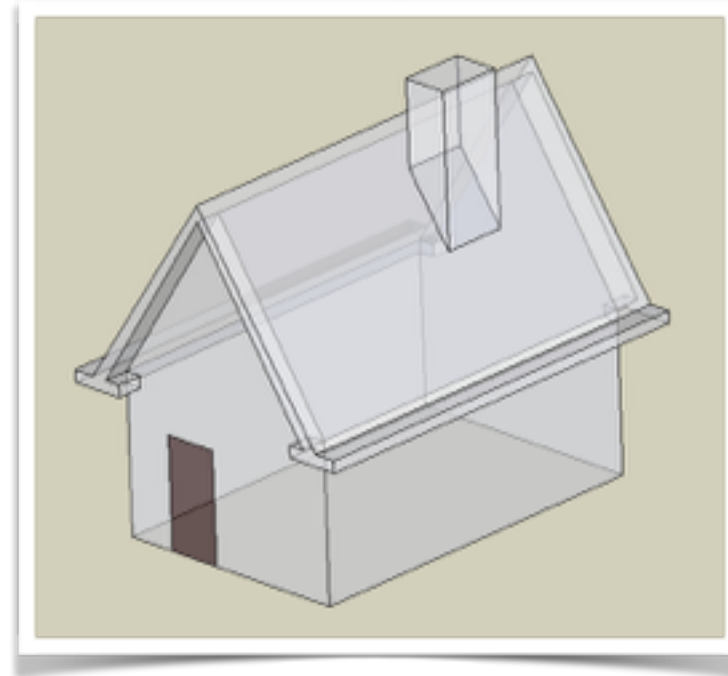
```
facet normal  $n_i$   $n_j$   $n_k$   
outer loop  
vertex  $v_{1x}$   $v_{1y}$   $v_{1z}$   
vertex  $v_{2x}$   $v_{2y}$   $v_{2z}$   
vertex  $v_{3x}$   $v_{3y}$   $v_{3z}$   
endloop  
endfacet
```

where each  $n$  or  $v$  is a floating point number in sign-mantissa 'e'-sign-exponent format, e.g., "-2.648000e-002". The file concludes with:

```
endsolid name
```

The structure of the format suggests that other possibilities exist (e.g., facets with more than one 'loop', or loops with more than three vertices) but in practice, all facets are simple triangles.

[source: Wikipedia]



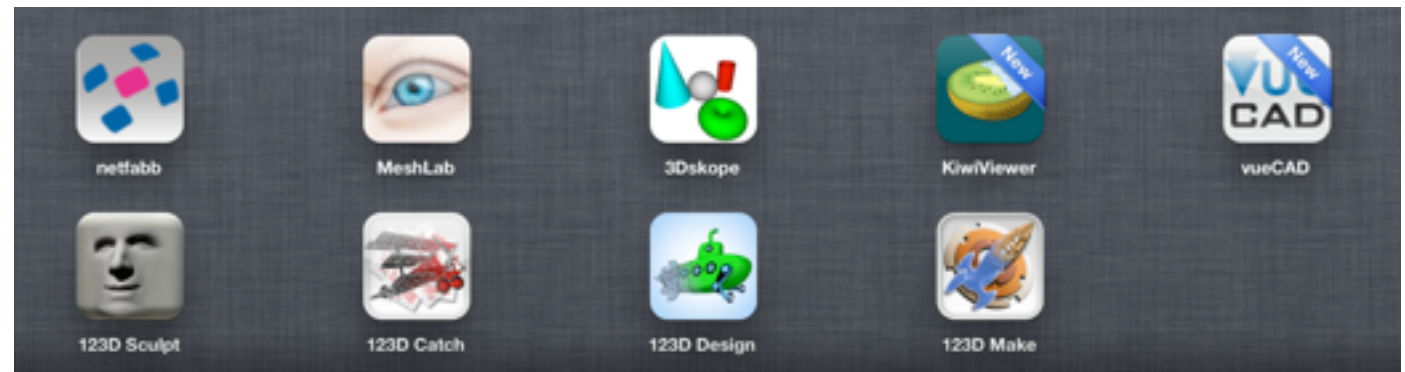
```
solid House  
facet normal 6.82119751824952e-17 -0.816496580927727 -0.577350269189624  
outer loop  
vertex 93660.6382456757 40.3376838970568 -161.045352763136  
vertex 92599.4905807017 244.743283455853 -450.118523884189  
vertex 92953.043971295 448.86742868779 -738.793658479011  
endloop  
endfacet  
facet normal 6.82119751824952e-17 -0.816496580927727 -0.577350269189624  
outer loop  
vertex 92599.4905807017 244.743283455853 -450.118523884189  
vertex 93660.6382456757 40.3376838970568 -161.045352763136  
vertex 92811.6226150577 122.268796316693 -276.913443127299  
endloop  
endfacet  
facet normal 6.82119751824952e-17 -0.816496580927727 -0.577350269189624  
outer loop  
vertex 92811.6226150577 122.268796316693 -276.913443127299  
vertex 93660.6382456757 40.3376838970568 -161.045352763136  
vertex 87861.8751467518 -2735.46923693036 3764.53844120011  
endloop  
endfacet  
facet normal 6.82119751824952e-17 -0.816496580927727 -0.577350269189624
```



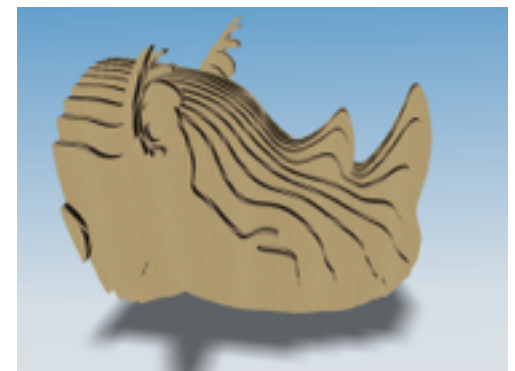
# Free iPad Apps for 3D modeling *with a “touch”*

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- netfabb (STL viewer only)
- MeshLab (STL viewer only)



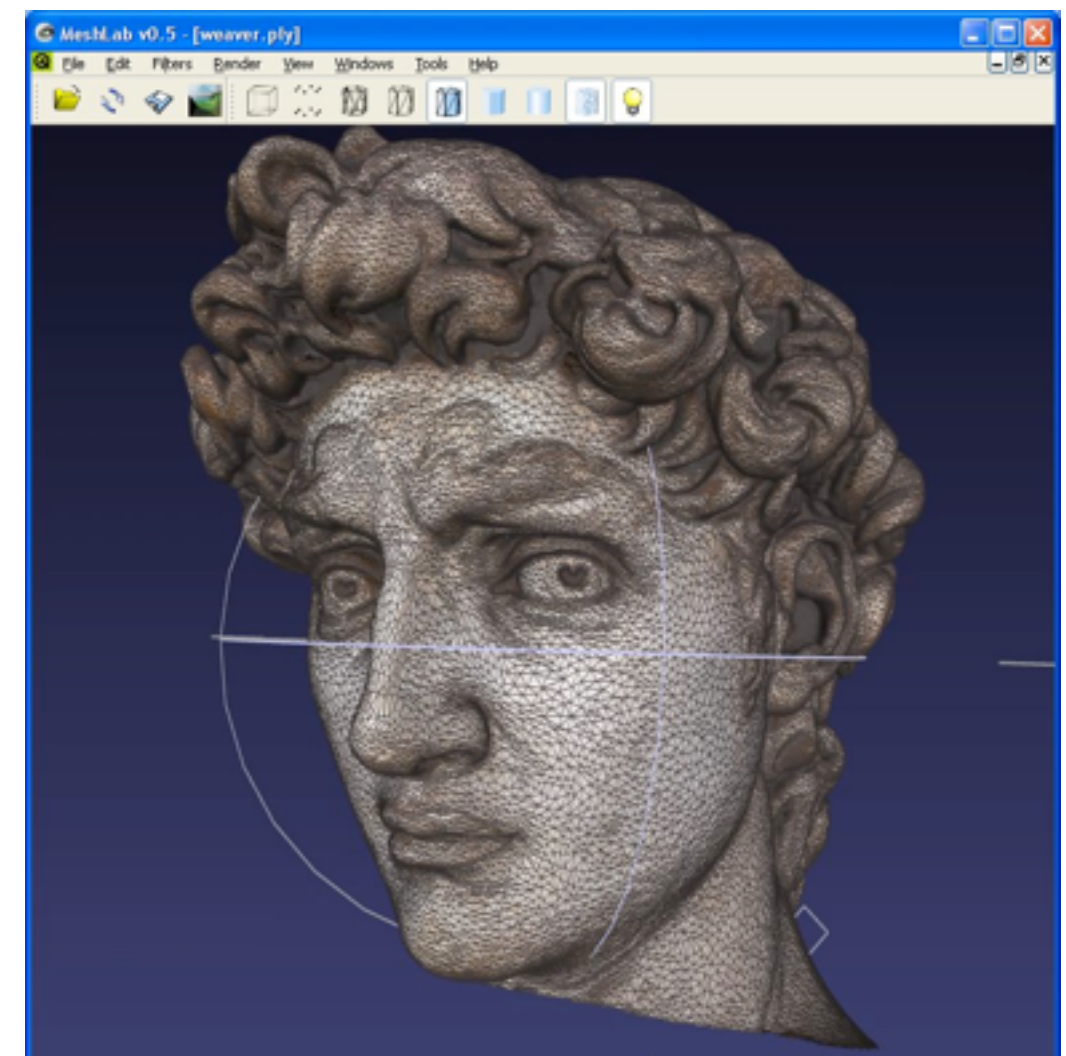
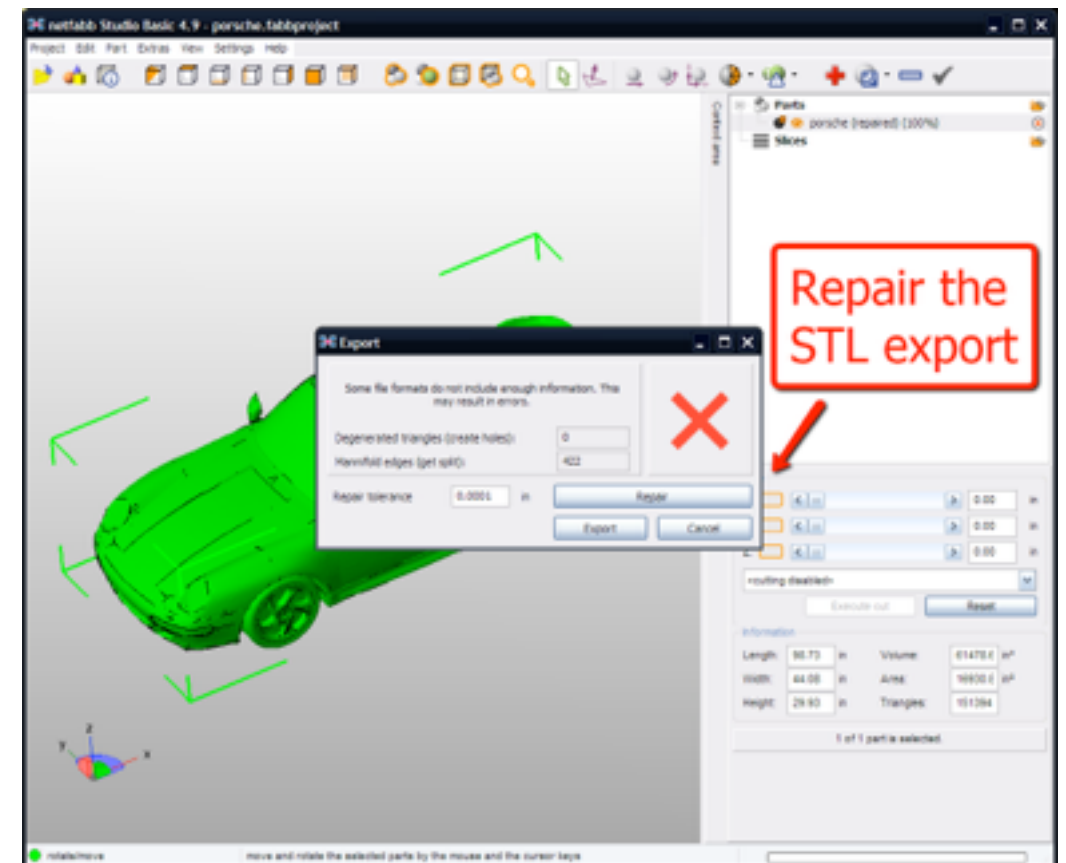
- other viewers (3Dskope, KiwiViewer, vueCAD)
- Autodesk: 123D Sculpt (*“rounded”*), 123D Design (*“squared”*)
- Autodesk 123D Catch (3D scanning with iPad/iPhone camera)
- Autodesk 123D Make (cardboard 3D models! ;-)





## #2 - Check & repair

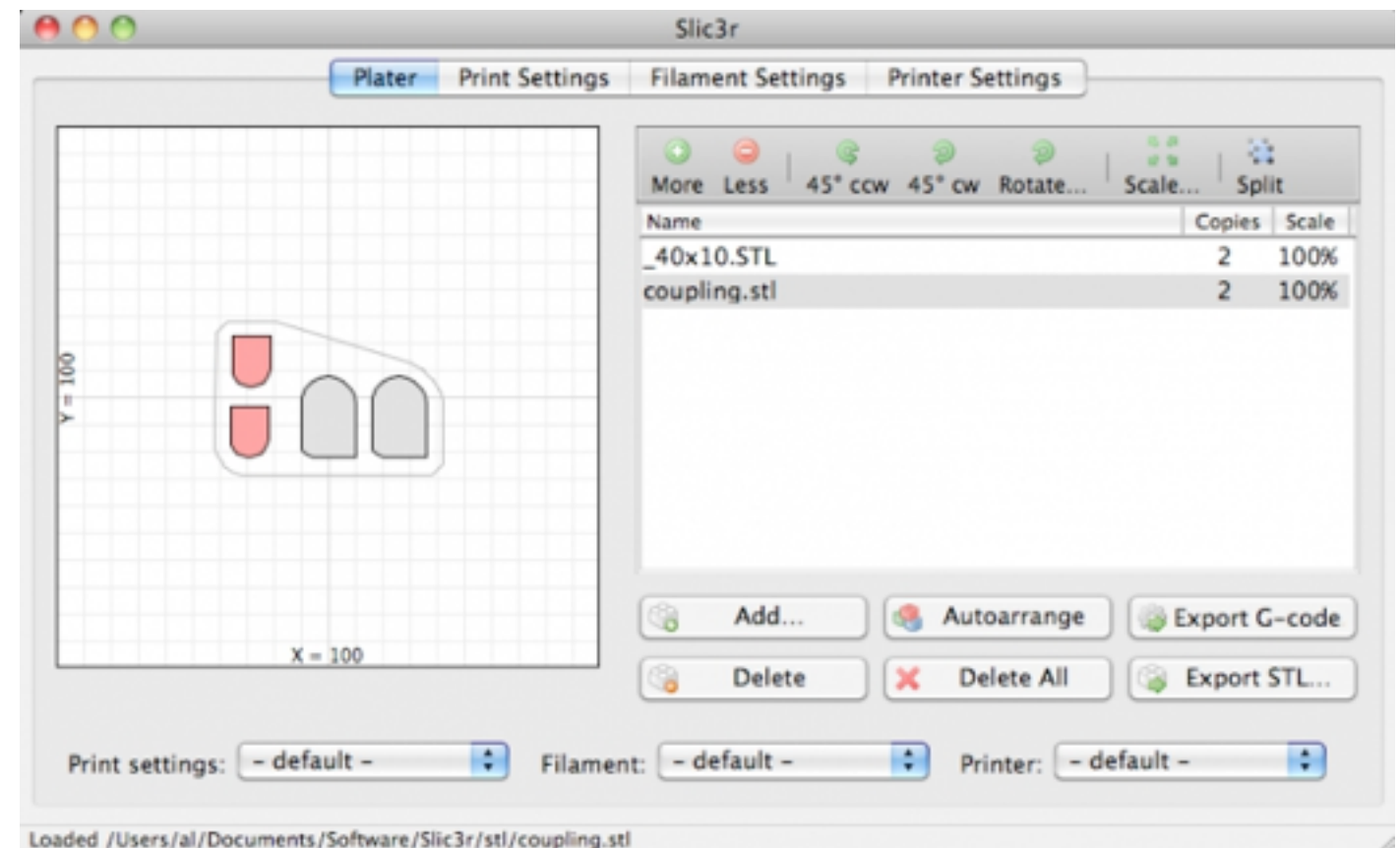
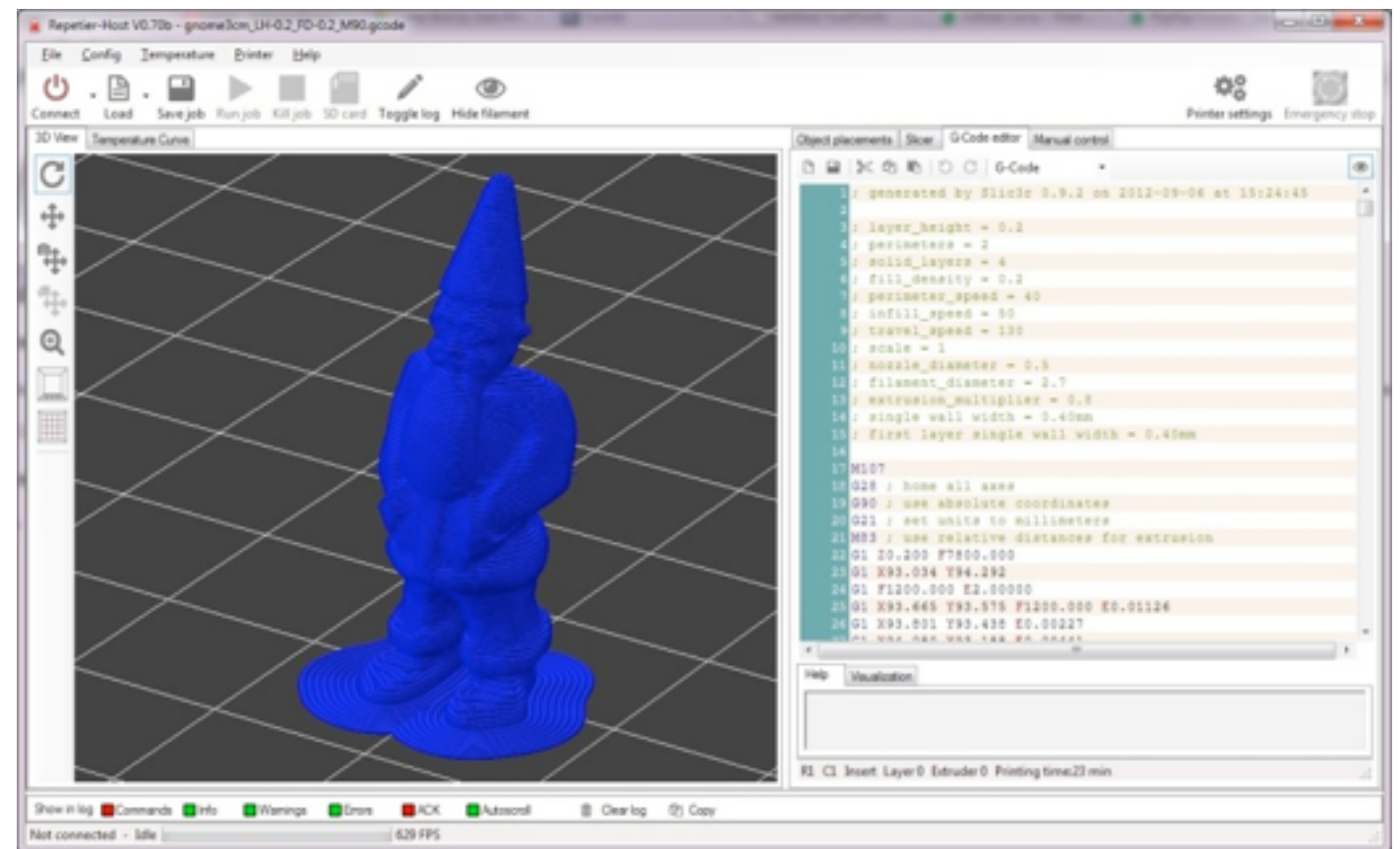
- The STL files that have been created by the modeling software may not be yet ready for printing, they should be checked for problems.
- Software for control and repair:
  - **netfabb** Studio Basic
  - **MeshLab** (conversion too)
- Software for visualization:
  - **Pleasant3D** (Mac only)





# #3 - Slice

- *Here comes the fun...*
- In order to print, the model (STL file) should be first converted into a set of instructions (a common one is called *G-code*) that tell to the printer how to move the printing head, when and how much plastic to extrude, etc.
- This is called **slicing**, and your model is now a *pile of layers*.
- This is the MOST CRITICAL part of the whole process, the final quality of the printed object is determined almost entirely by a correct choice of values for the many different *slicing parameters*.





# An example: Slic3r

Slice...

Save configuration...

Load configuration...

Remember to check for updates at <http://slic3r.org>

Vers

Print Settings

Printer and Filament

Start/End GCODE

Advanced

Transform

Scale:1

Rotate (°):0

Copies along X:1

Copies along Y:1

Distance between copies:6

Print settings

Perimeters:3

Solid layers:3

Fill density:0.4

Fill angle (°):45

Fill pattern:rectilinear

Solid fill pattern:rectilinear

Accuracy

Layer height (mm):0.4

First layer height ratio:1

Infill every N layers:1

Skirt

Loops:1

Distance from object (mm):6

Retraction

Length (mm):1

Lift Z (mm):0

Speed (mm/s):30

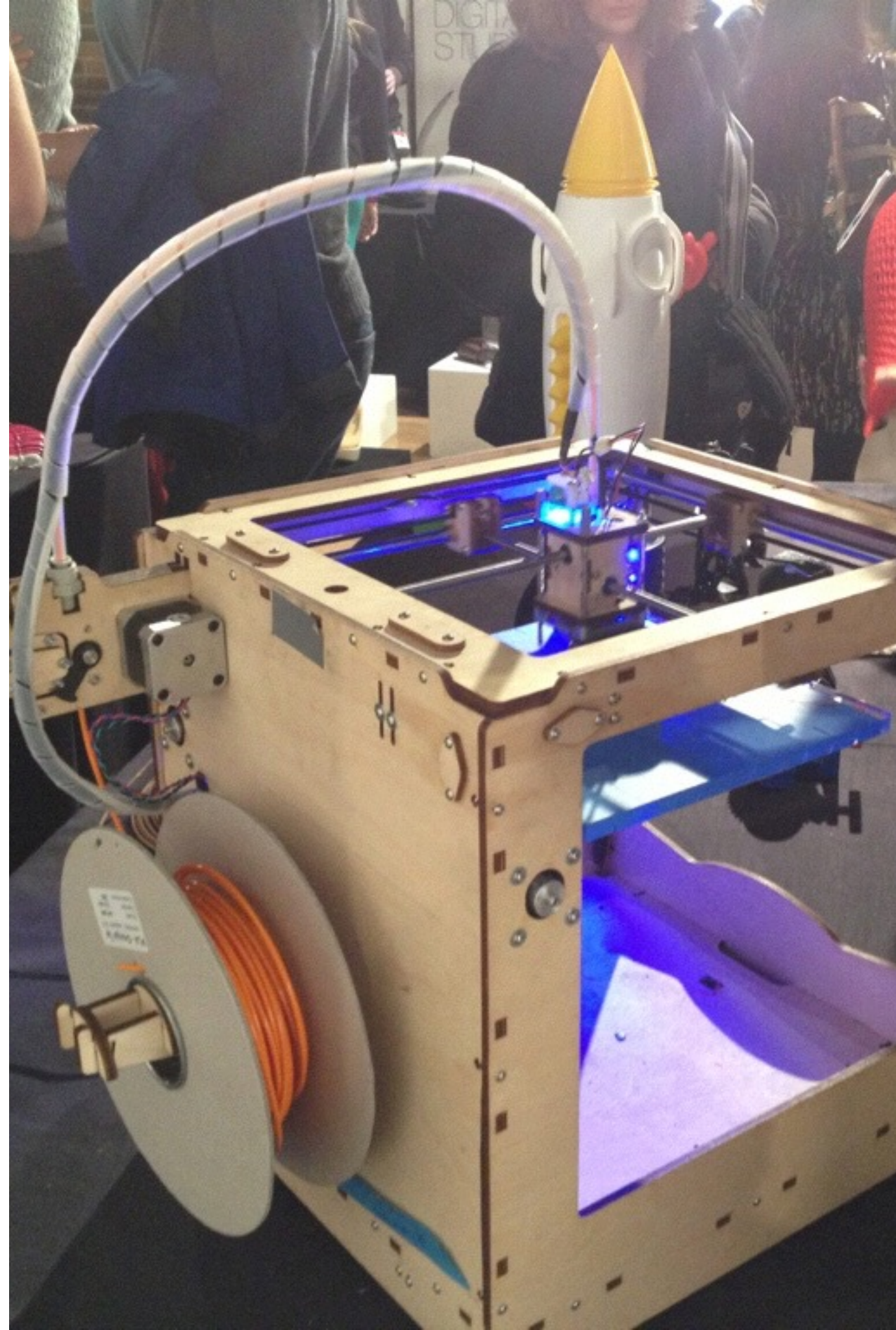
Extra length on restart (mm):0

Minimum travel after retraction (mm):2

## #4 - Prepare the printer

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- calibrate (level) the platform (printing bed) and clean it
- pre-heat the printing head
- load the plastic filament into the extruder
- extrude some plastic, in order to fill the nozzle
- start the print ;-)

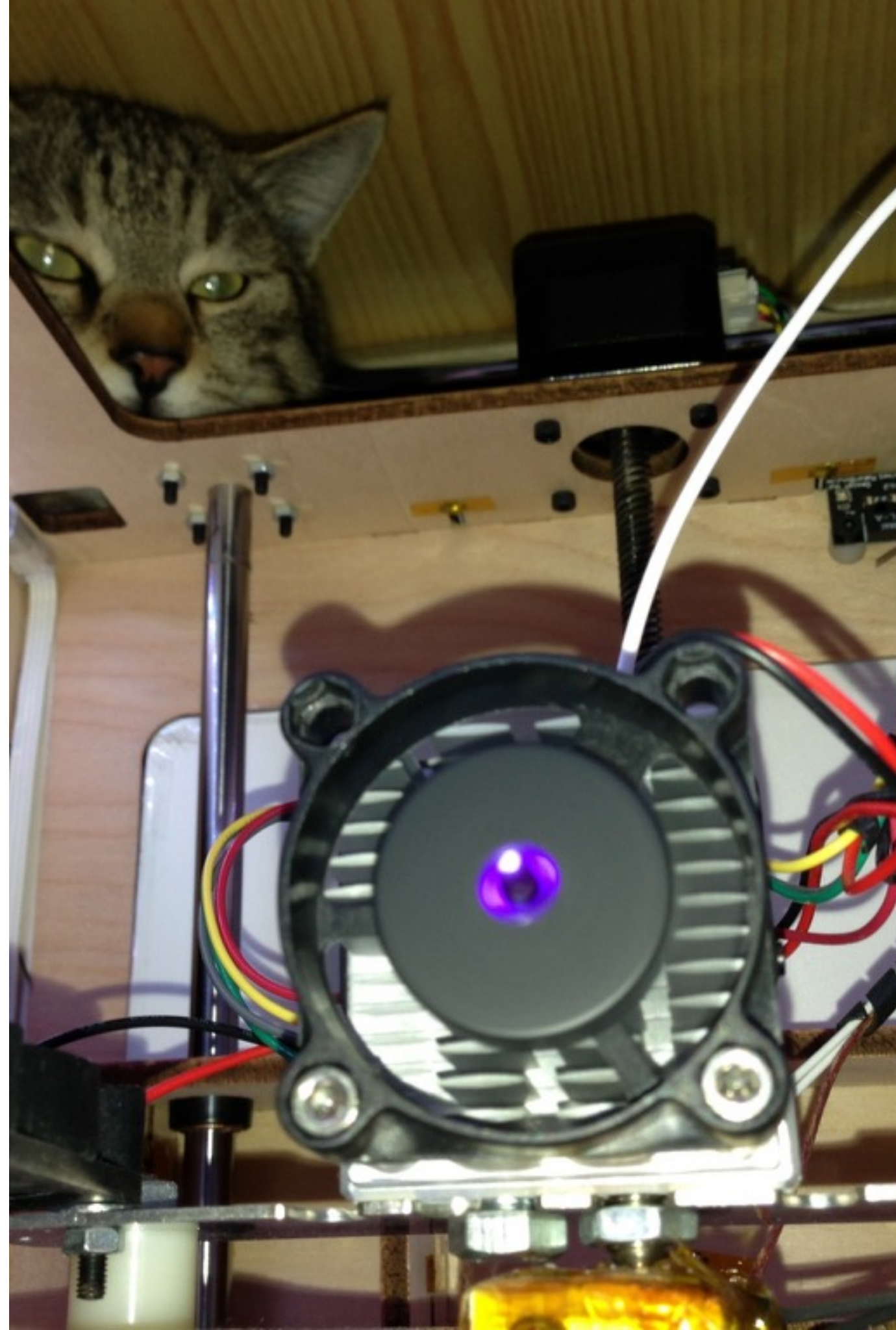




## #5 - Wait until finished

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- Printing time for a small object can be 10-20 minutes.
- For an object the size of an apple, can be up to 1 hour and more (it depends on resolution, infill, and printer speed).
- Bigger objects can take 10+ hours, complex ones even 20+ hours...
- May be dangerous to leave a 3D printer unattended when printing (temp > 200°C, melted plastic, electricity, moving parts, wooden frame...).

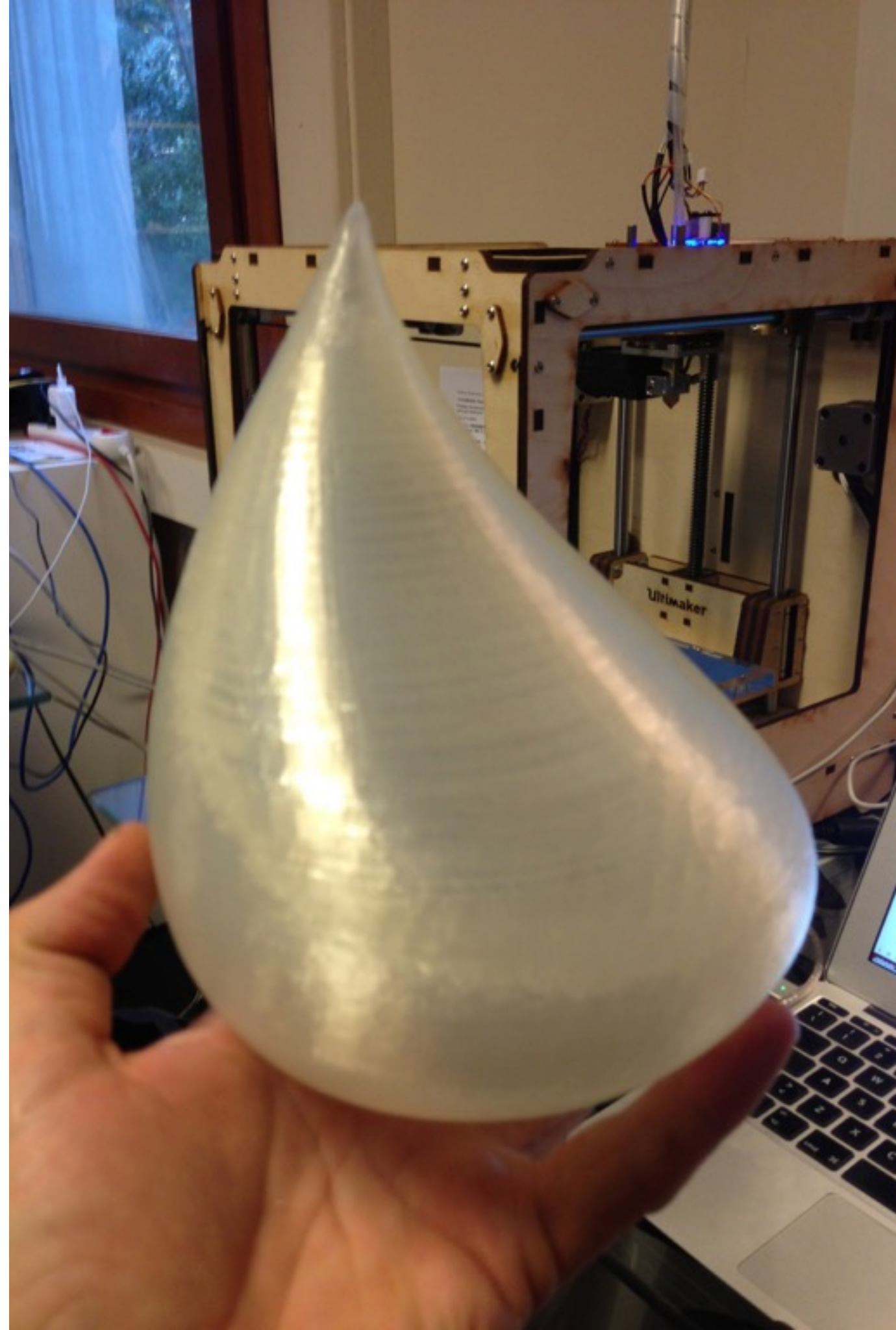




## #6 - Finishing

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- After the print, you may want to give a few minutes for the object to cool down (it will be easier to detach it from the bed).
- You may have to remove raft/support structures.
- If needed, the object surface can be smoothed by using sandpaper (it may ruin the finishing), a chemical solvent (i.e. Acetone for ABS), heat (hot air blower) or a coating paint.







Over 4,000,000 tons of plastic waste is floating in a huge patch in the Pacific Ocean, growing steadily every year

# A world of plastic

don't pollute,  
3D-print!





# Many types of plastics

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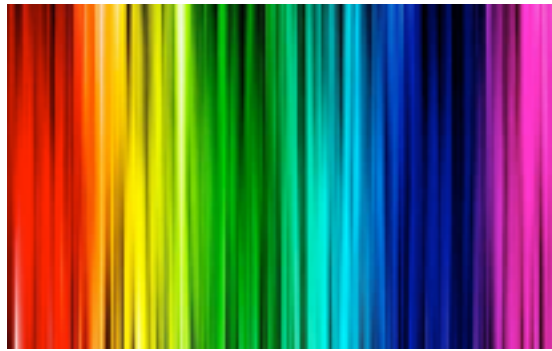
- **ABS** (Acrylonitrile Butadiene Styrene), petroleum based plastic (used for the Lego™ bricks)
- **PLA** (Polylactic Acid or Polylactide), a *biodegradable* plastic made out of plant starch
- **Nylon** (®Taulman 618/645 or “*grass cutter*” filament –available at lower cost)
- **PVA** (Polyvinyl Alcohol), *water-soluble*
- **PS** (Polystyrene), used for plastic cups/dishes
- **HIPS** (High Impact Polystyrene, *soluble in Limonene*)
- **PET** (Polyethylene terephthalate), used in most water bottles
- **others**: soft/flexible, temperature-sensitive, wood-based, stone-like, conductive, etc...





# Filament

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- Filament comes in two standard diameters, **1.75 mm** and **3.0 mm**. The 3.0 mm filament is somehow an older standard and is slowly being upstaged by the 1.75 mm because it can be pushed slightly more easily, controlled a little better and sometimes leaves fewer tails hanging off the sides of your object.
- Cost: around 30\$ (25€) per kg.
- 1g of printed object ~ 0.03 cents
- active development of systems for **low-cost filament production “at home”**, starting from plastic pellets or –even better– from recycling of plastic waste.





# Recycling plastic

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[www.perpetualplasticproject.com](http://www.perpetualplasticproject.com)

- make 3D-printed objects from recycled plastic





# Recycling plastic

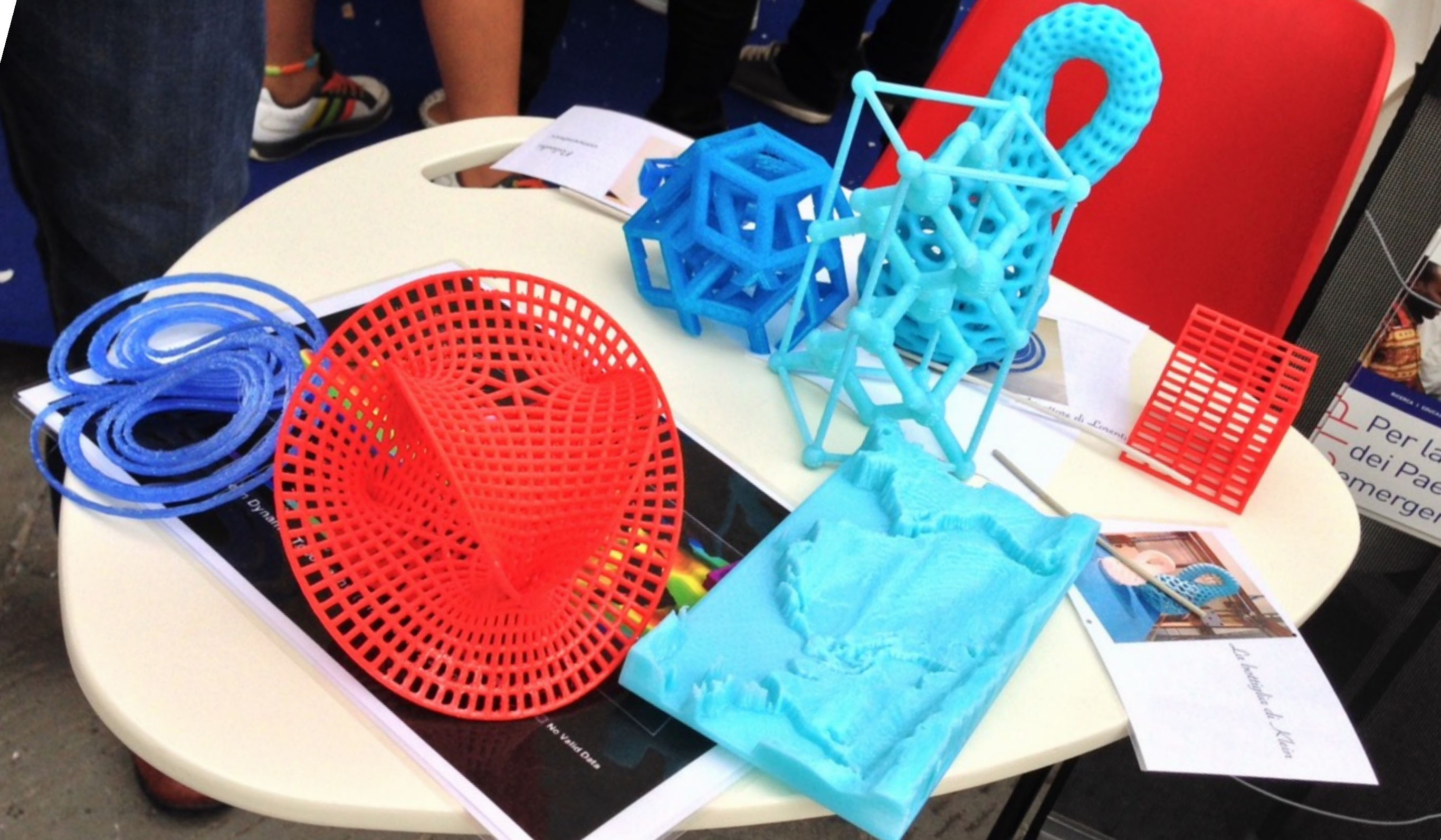
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[www.perpetualplasticproject.com](http://www.perpetualplasticproject.com)

- make 3D-printed objects from recycled plastic







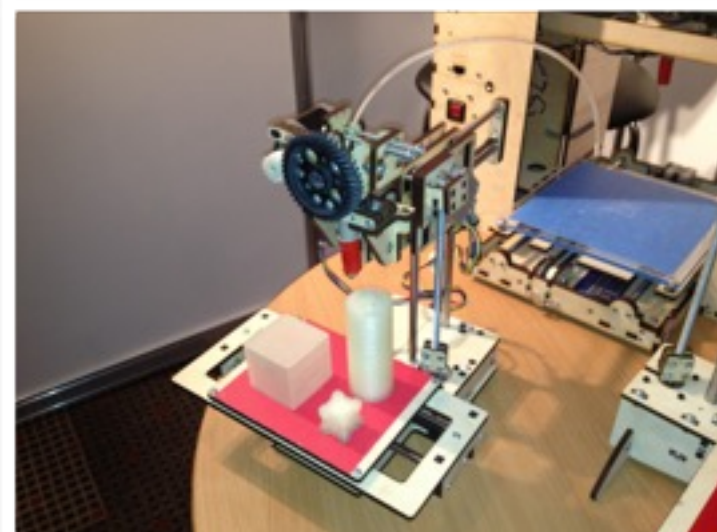
Scientific applications  
of low-cost 3D printing

... And other interesting things!



# Small is beautiful

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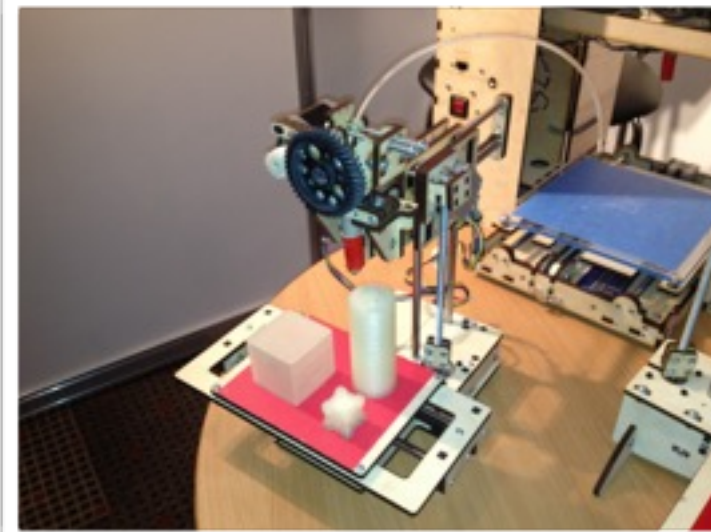




# Small is beautiful

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- Common low-cost 3D-printers can print objects with dimensions of **less than 20x20x20cm (approx.)**

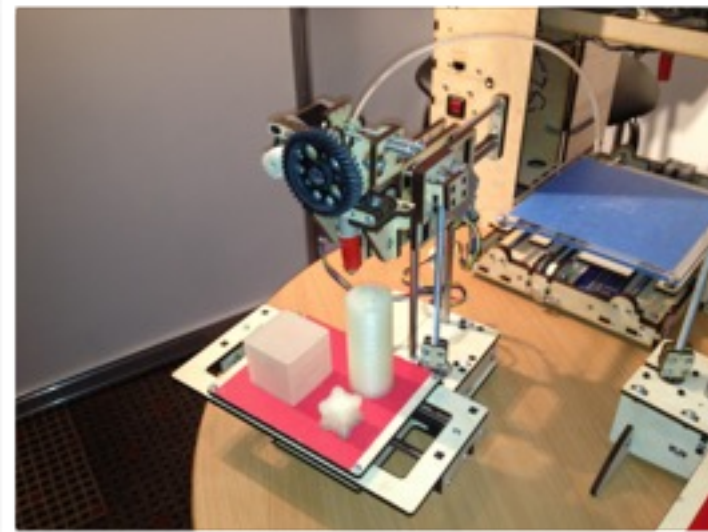




# Small is beautiful

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- Common low-cost 3D-printers can print objects with dimensions of **less than 20x20x20cm (approx.)**
- In some models isn't very difficult to increase the vertical size. Horizontal limits are harder to break.

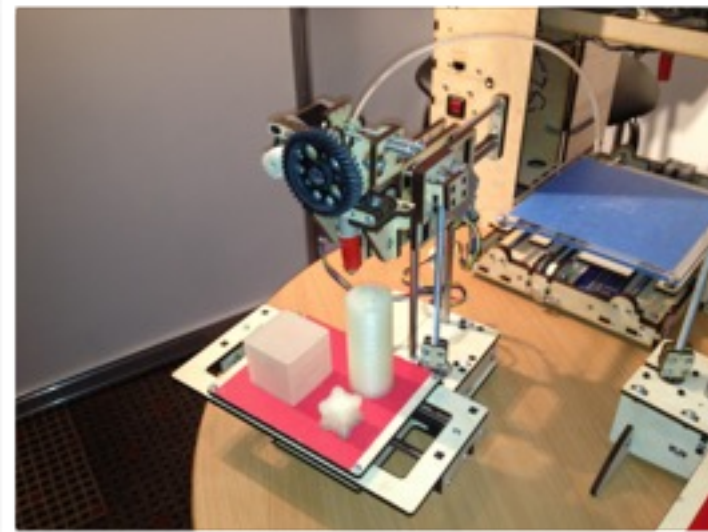




# Small is beautiful

---

- Common low-cost 3D-printers can print objects with dimensions of **less than 20x20x20cm (approx.)**
- In some models isn't very difficult to increase the vertical size. Horizontal limits are harder to break.
- It is still possible to build larger object by combining together multiple parts (with glue, screws or joints).






# Cloning objects

---

- Combining 3D scanners with 3D printers, it becomes possible (and affordable) to make copies (1:1 or scaled) of objects (even at a distance!)



A model (left) was digitally acquired by using a  **3D scanner**, the scanned data processed using **MeshLab**, and the resulting **3D model** used by a **rapid prototyping** machine to create a resin replica (right)



# Cloning objects

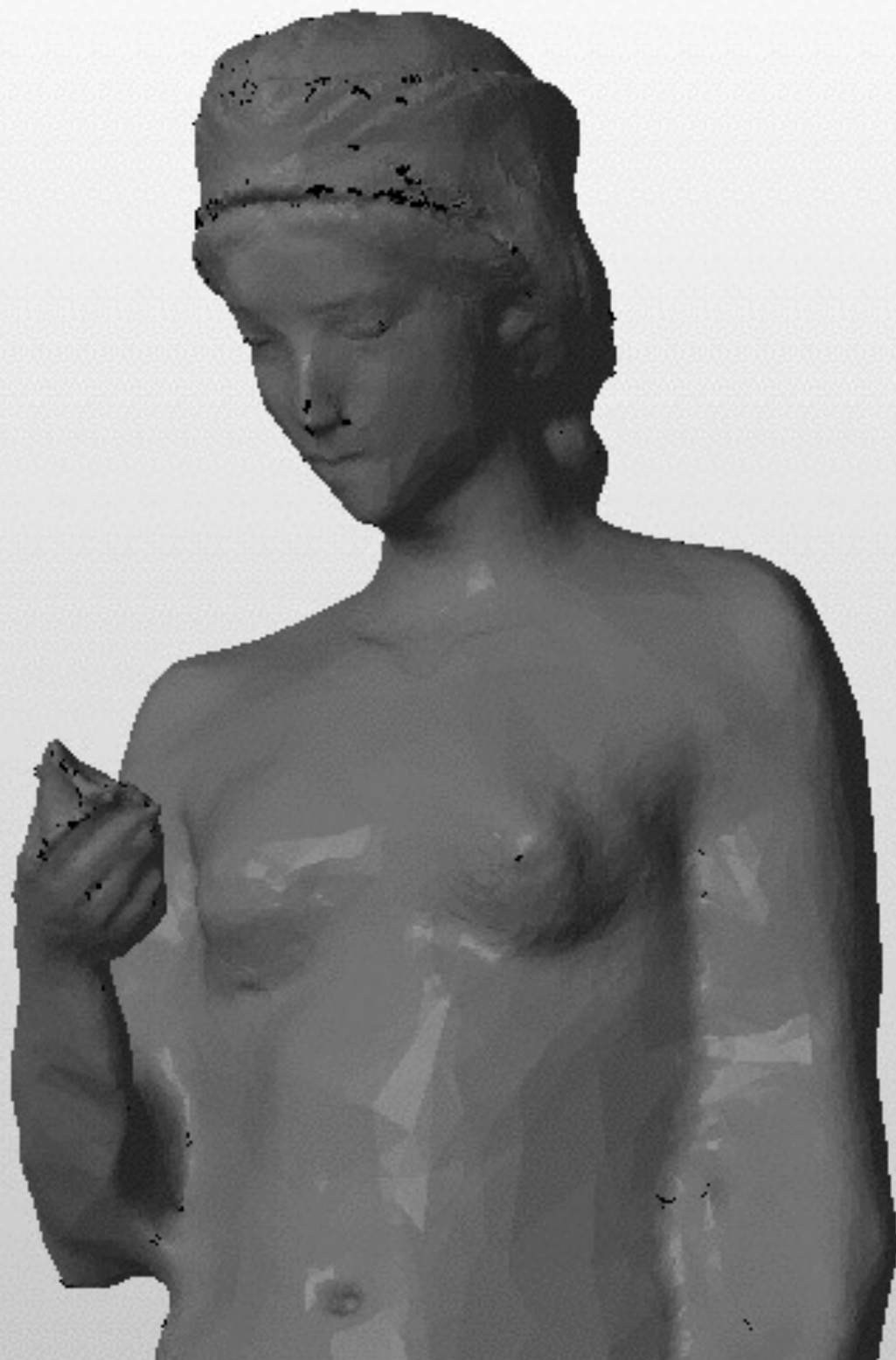
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A model (left) was digitally acquired by using a [3D scanner](#), the scanned data processed using [MeshLab](#), and the resulting [3D model](#) used by a [rapid prototyping](#) machine to create a resin replica (right)





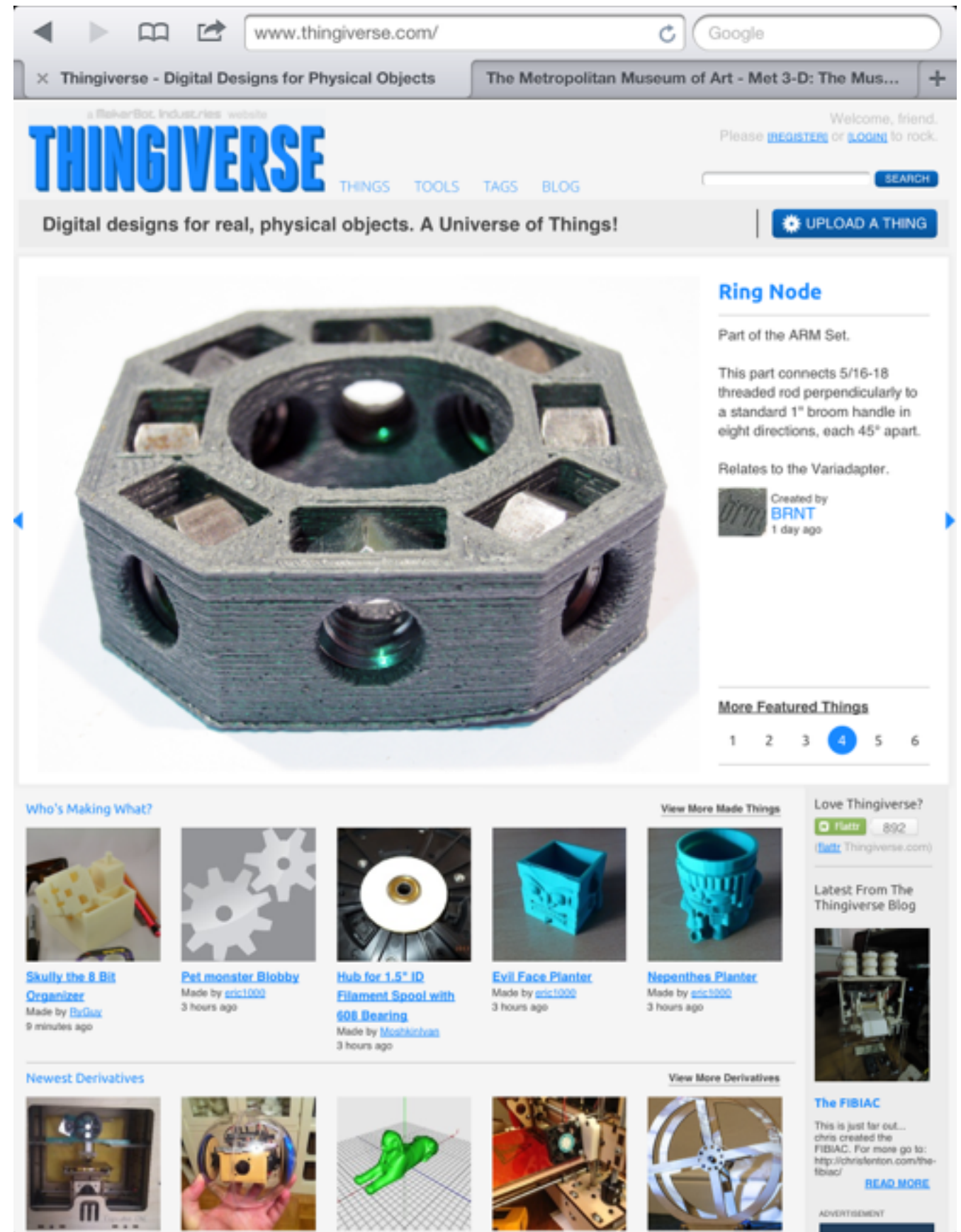
During the summer of 2012, the Metropolitan Museum of Art held an event to make 3D scans and prints of works from throughout the museum. Participants used digital cameras and Autodesk's 123D Catch to generate the 3D models, and then printed them using MakerBot Replicators.

***Met3D***



# Making *new* objects

- 3D printing isn't just about *copying* objects, but also about *creating new things*, that are impossible (or expensive, or difficult) to make with other technologies. **At home!**







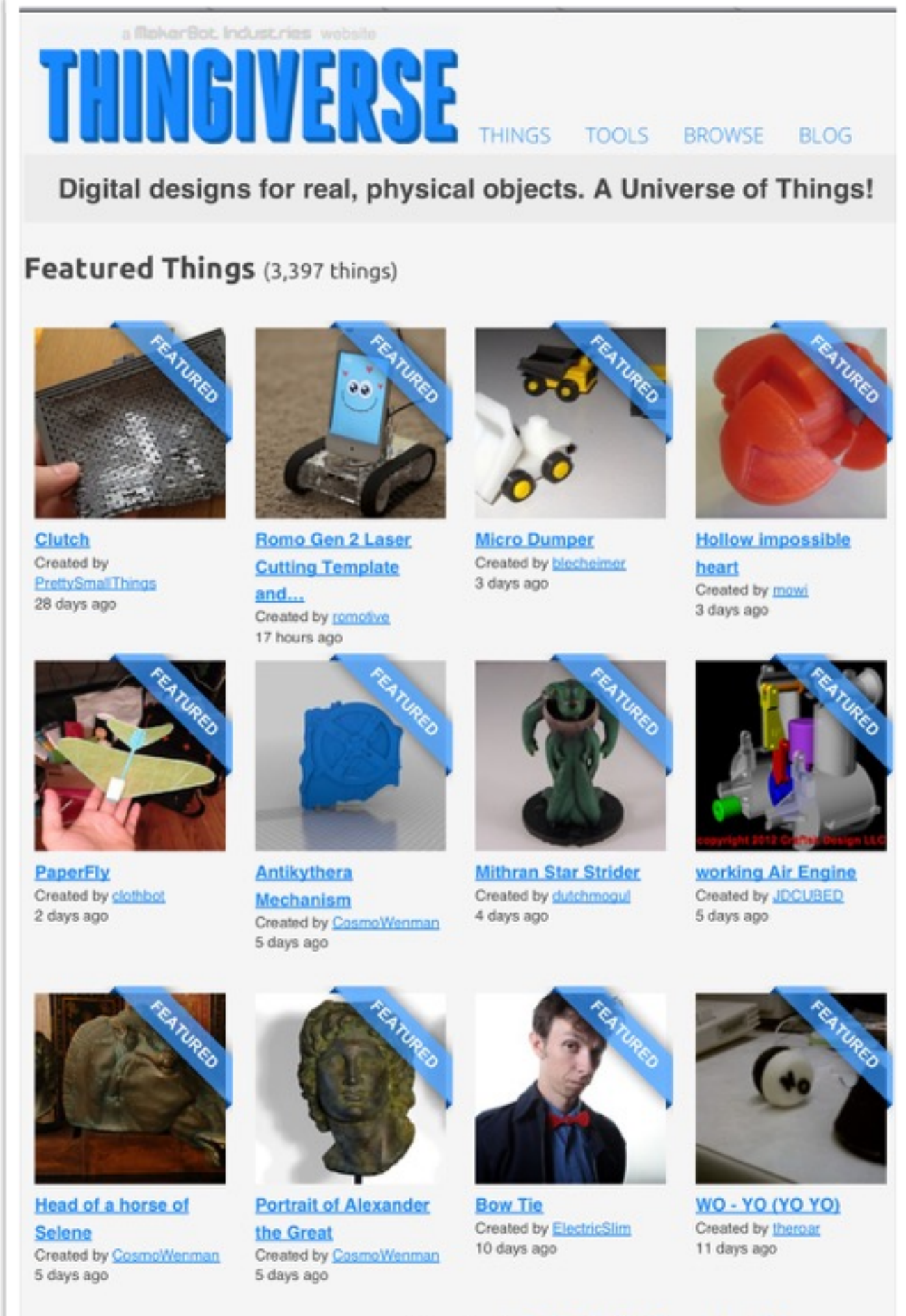
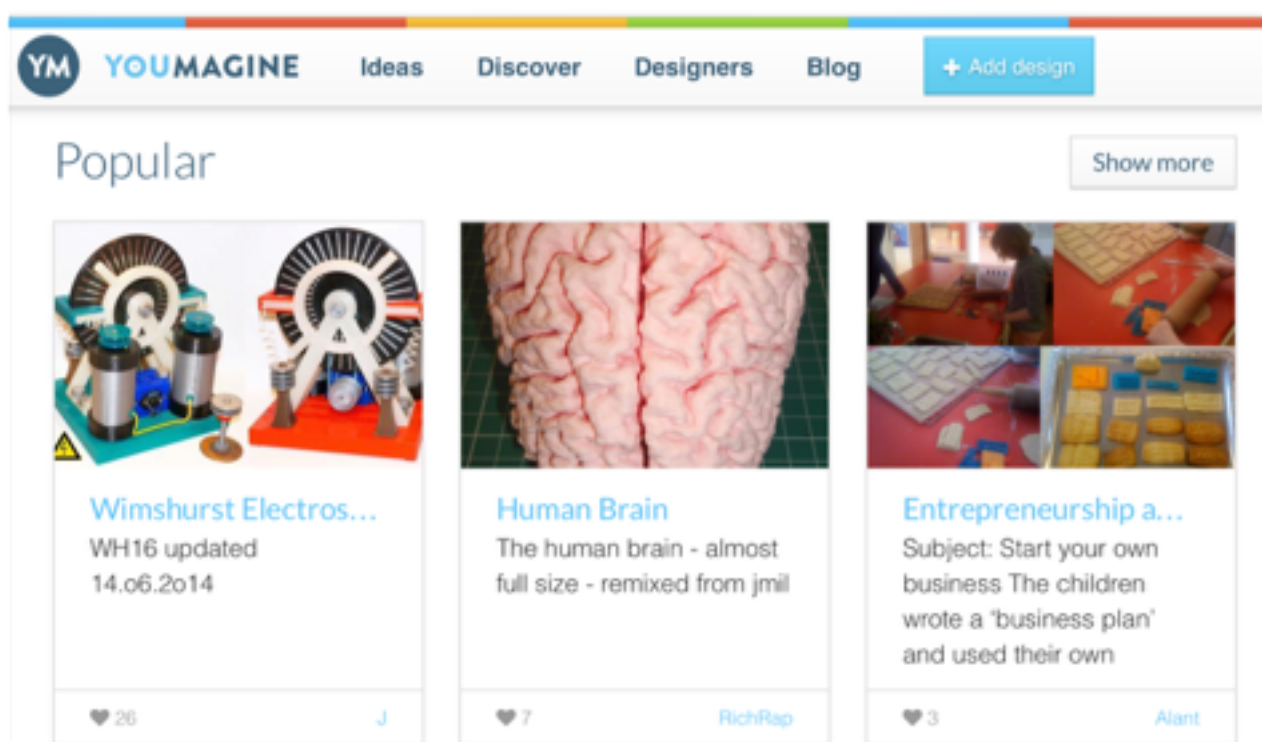






# Thingiverse & C.

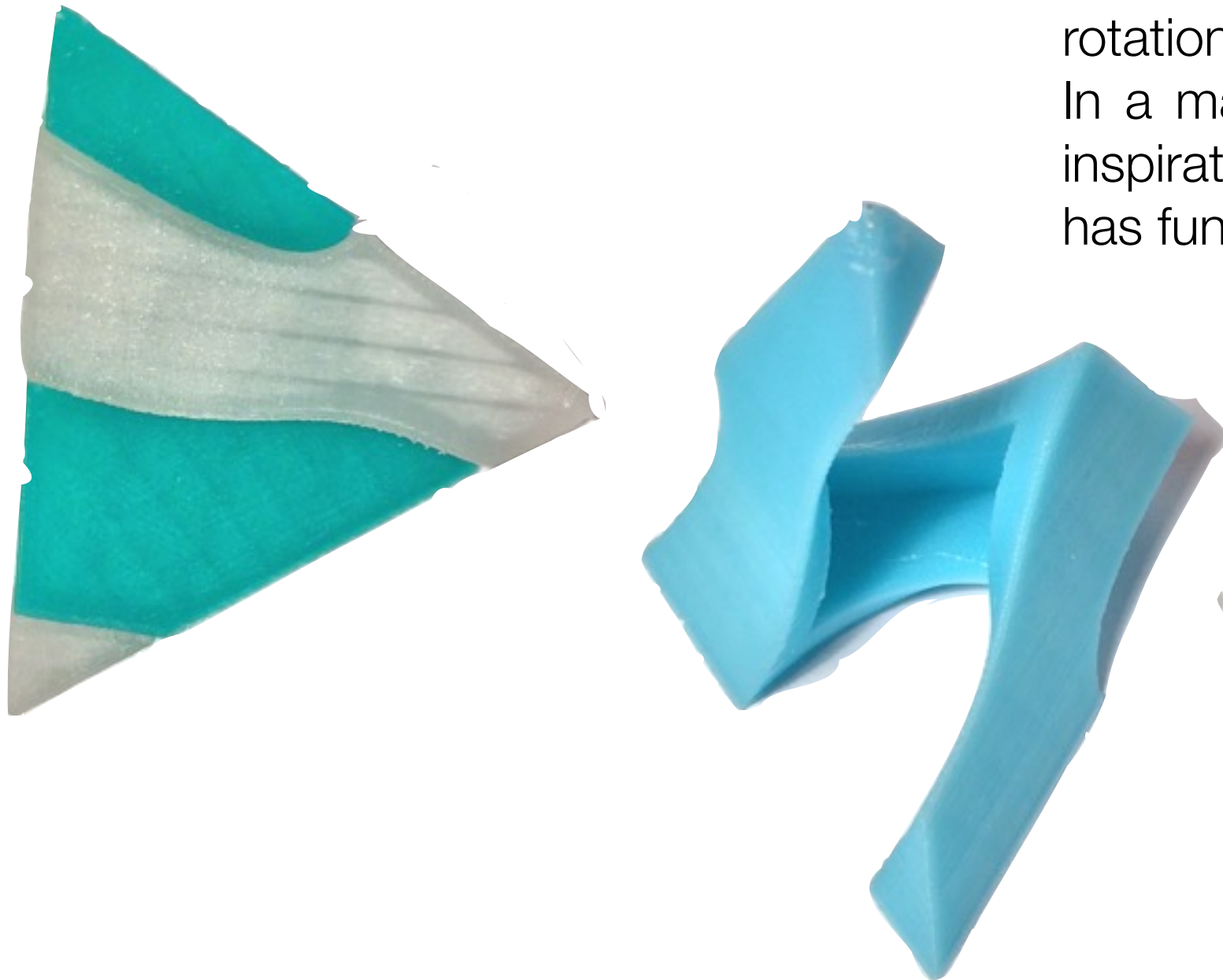
- [www.thingiverse.com](http://www.thingiverse.com)
- [www.youmagine.com](http://www.youmagine.com)
- People sharing a LOT of 3D (often editable) object models
- all are free, with open licenses





These puzzles challenge anyone who plays with them to think about combining the geometric transformations of translation and rotation in new ways.

In a math class, they also provide inspiration to see that mathematics has fun and creative applications.



Screw-puzzle  
by George Hart

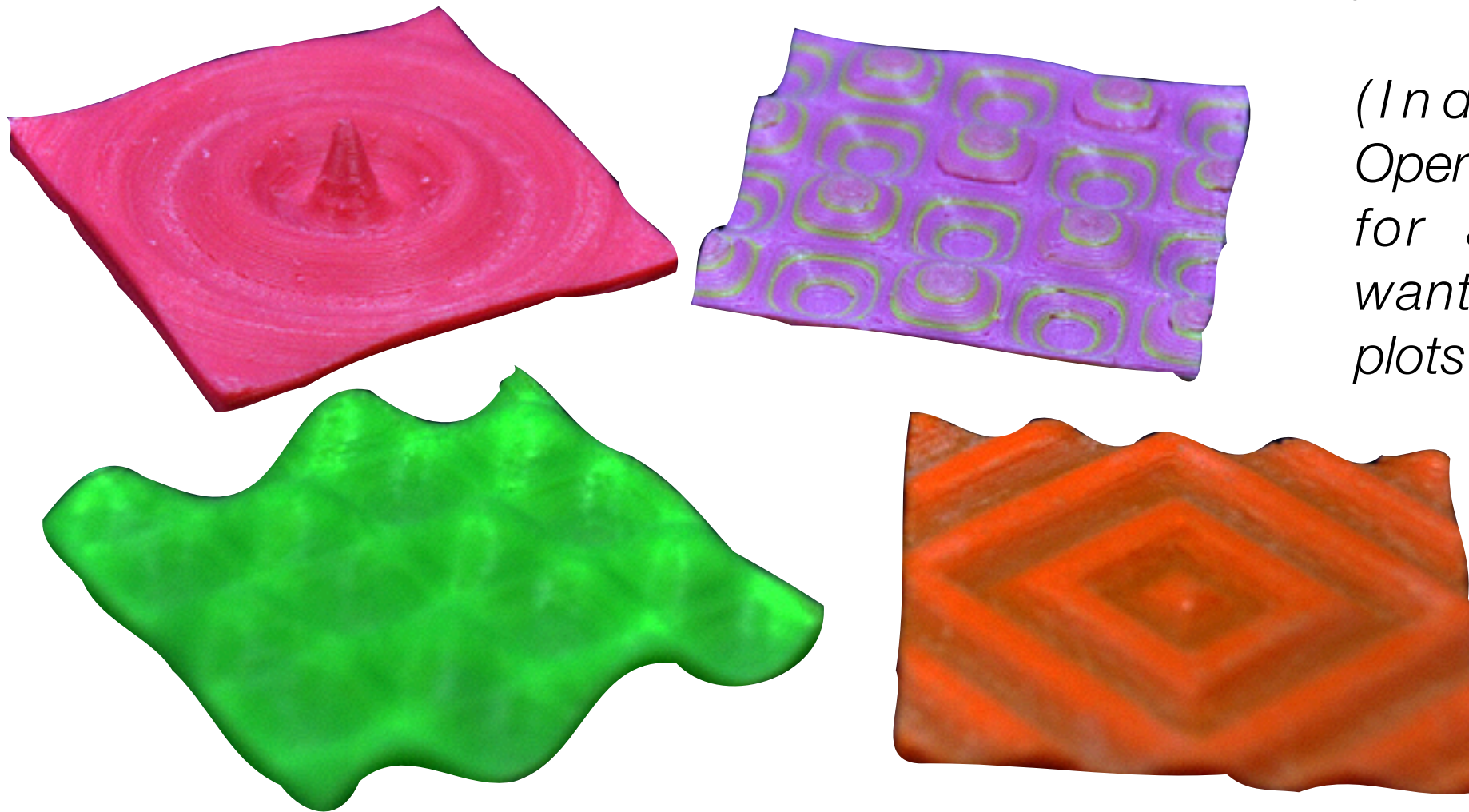
<http://www.thingiverse.com/thing:186372>



*“Could there be anything more fun than drawing 3D surface plots?”*

*Yes, you can 3D print 3D surface plots and hold them in your own hands!*

*(Indeed, I wrote this OpenSCAD program in 2011 for a math teacher who wanted some tangible 3D plots for a blind student.)”*



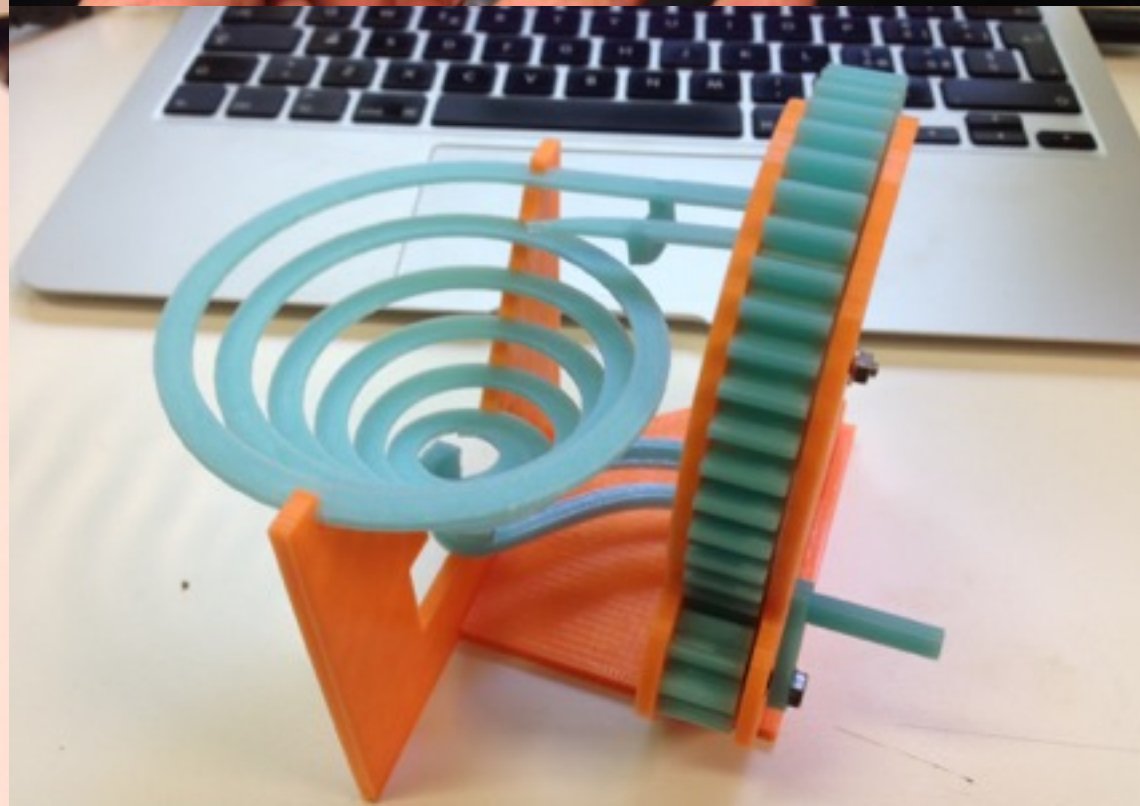
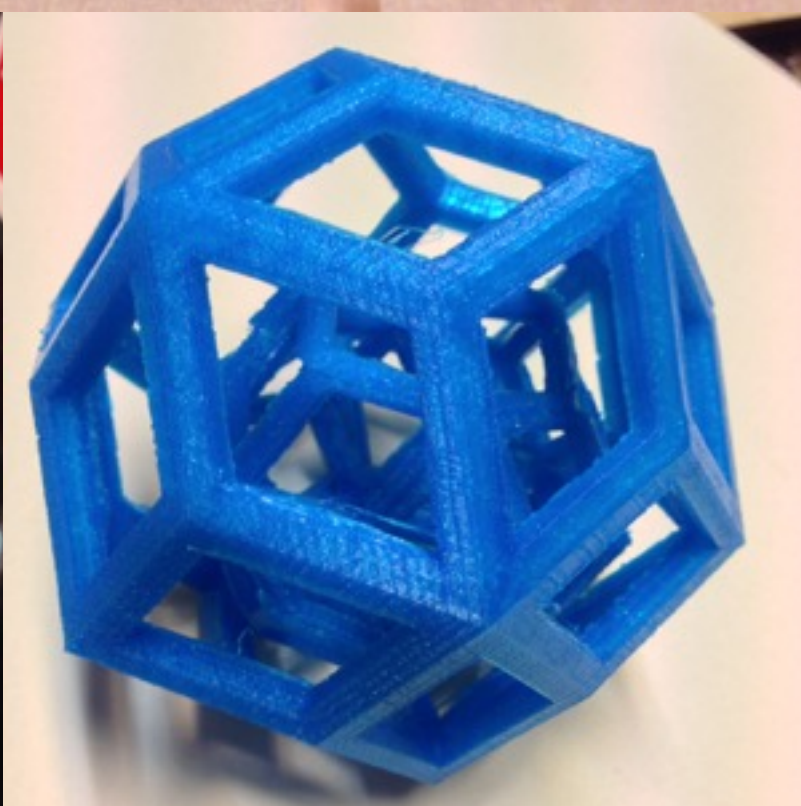
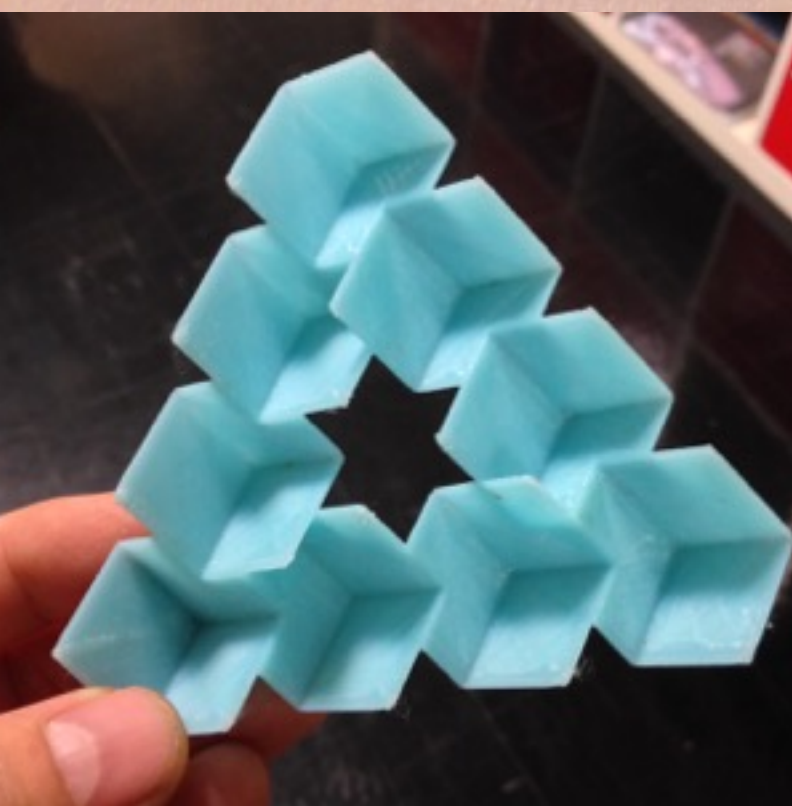
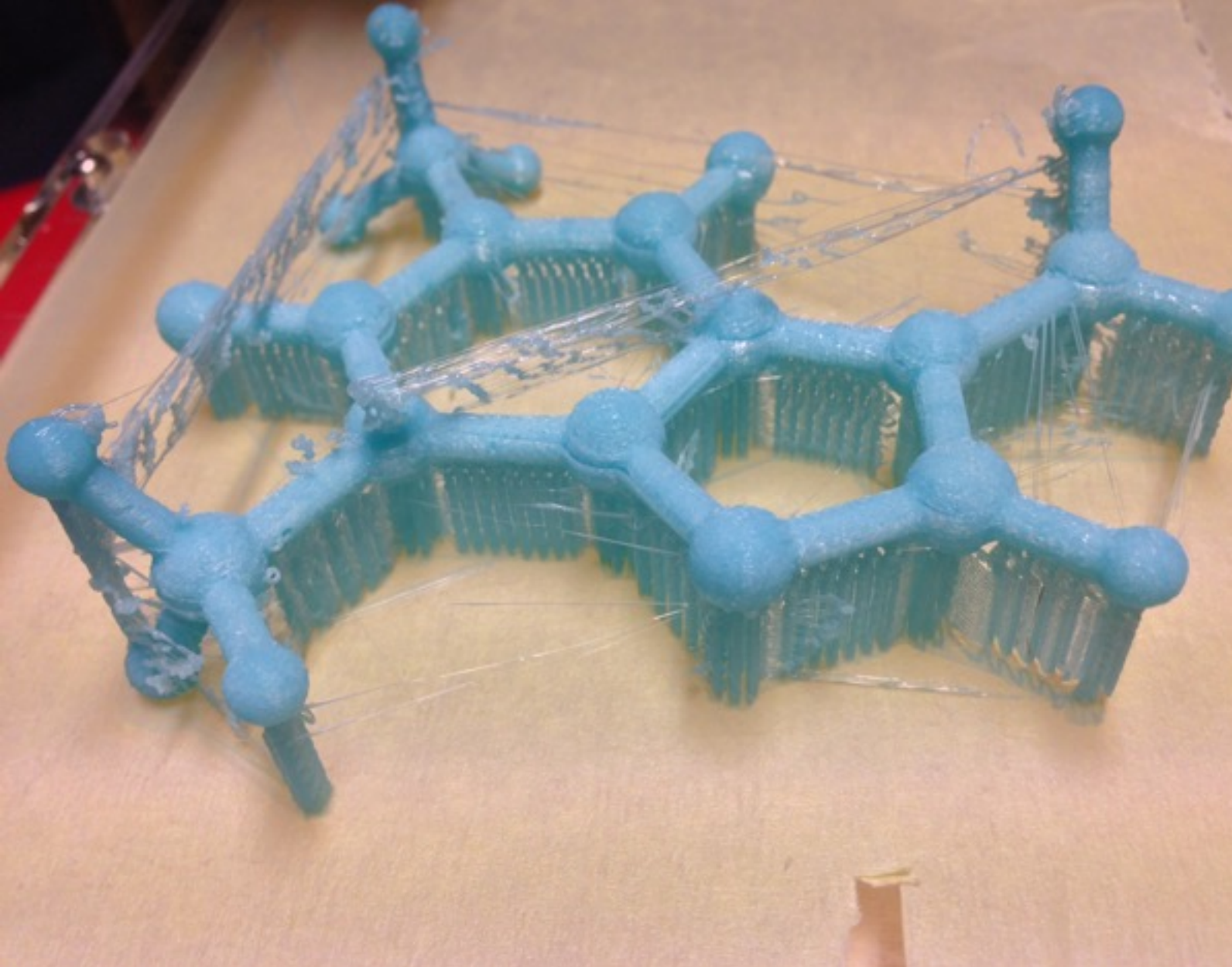
OpenSCAD 3D Surface  
Plotter

<http://www.thingiverse.com/thing:24897>









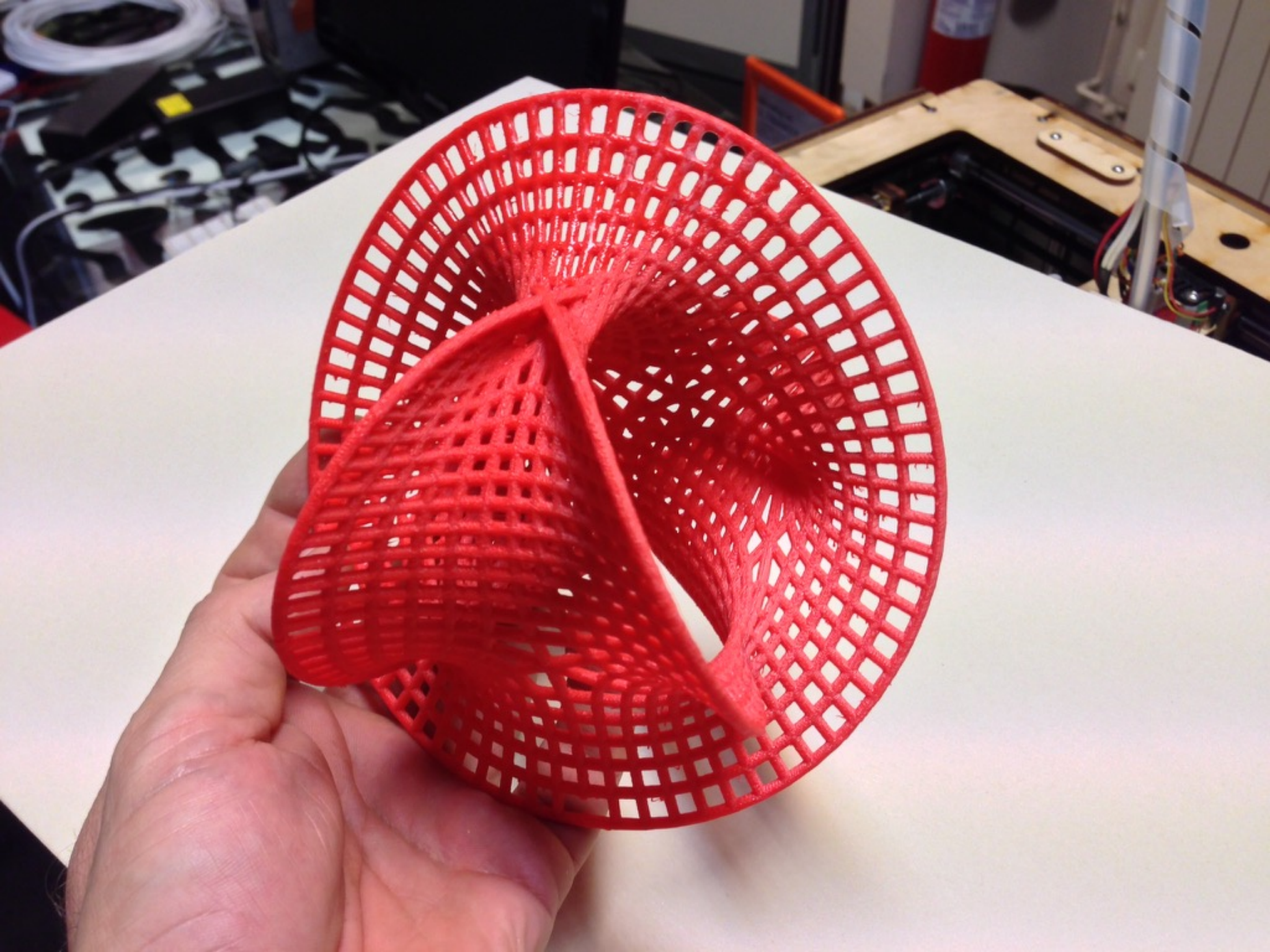




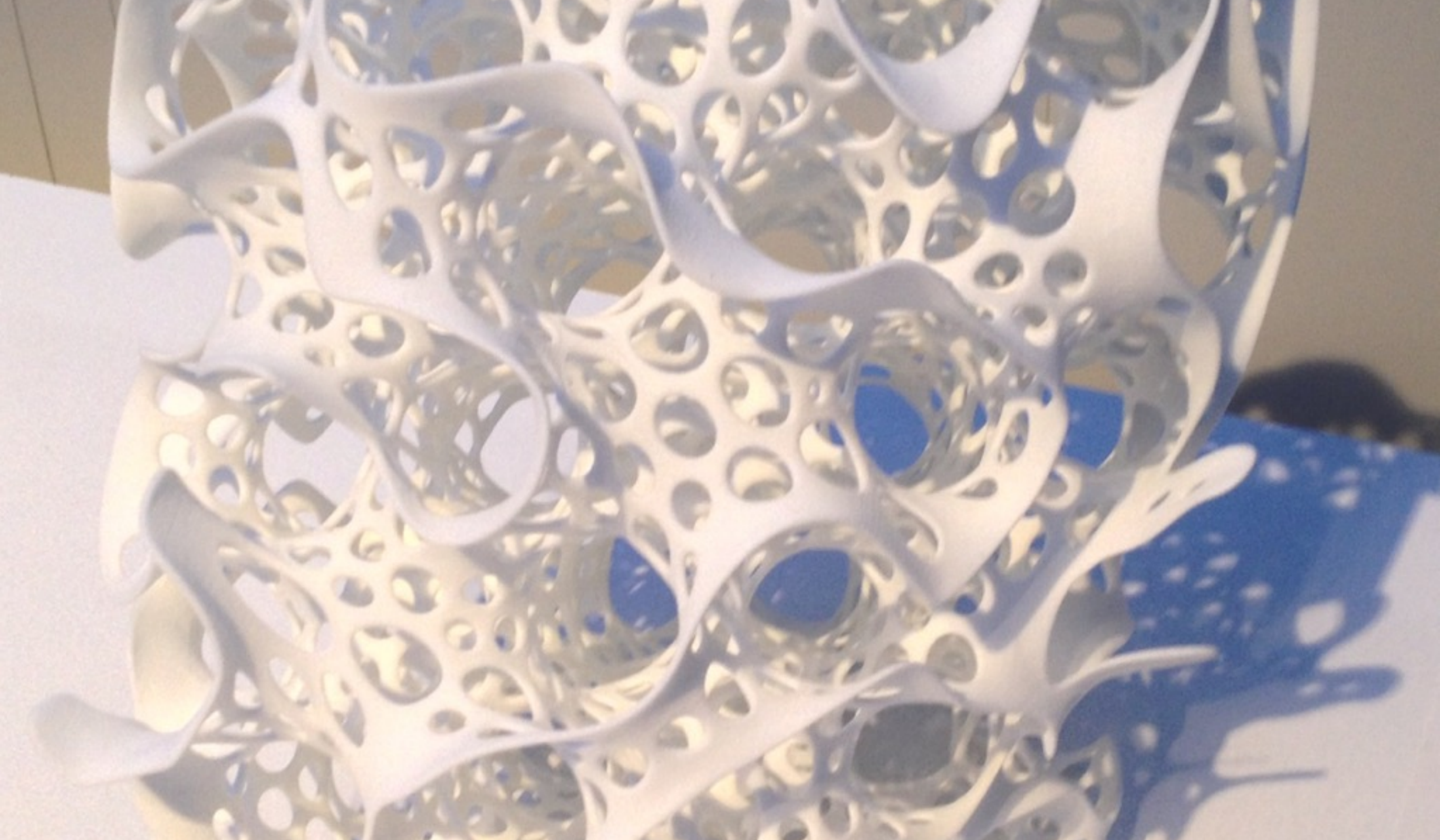












Low-cost 3D printers for  
scientific dissemination and  
for education?

... we are investigating



# Why? Because **2<3** ;-)

---

- 1 image > 1000 words
- 1 object we can touch > 1000 images !!!
- An object = invaluable tool for physically disabled students
- Printing complex objects is cheap (laboratory parts?)
- Remote communications: from bits to atoms...



First International Workshop on  
***"Low-cost 3D Printing for Science,  
Education and Sustainable Development"***  
May 6 - 8, 2013  
(Miramare - Trieste, Italy)

The Science Dissemination Unit (SDU) of the Abdus Salam International Centre for Theoretical Physics (ICTP) will organize First International Workshop on ***"Low-cost 3D Printing for Science, Education and Sustainable Development"***, to be held at the ICTP, Trieste, Italy from May 6 to 8, 2013.



New, low-cost, three-dimensional printing technologies are providing exciting opportunities for research, education and humanitarian projects for the developing world.

**DIRECTORS**

**E. CANESSA**  
(ICTP-SDU)

**C. FONDA**  
(ICTP-SDU)

**M. ZENNARO**  
(ICTP-SDU)



# An article on Nature

<http://www.nature.com/news/science-in-three-dimensions-the-print-revolution-1.10939>



NATURE | NEWS FEATURE

## Science in three dimensions: The print revolution

Three-dimensional printers are opening up new worlds to research.

Nicola Jones

04 July 2012



Research labs use many types of 3D printers to construct everything from fossil replicas to tissues of beating heart cells. Arthur Olson's team at the Scripps Research Institute in La Jolla, California, produces models of molecules; some are shown here partway through the printing process.



BY NICOLA JONES

### THREE-DIMENSIONAL PRINTERS ARE OPENING UP NEW WORLDS TO RESEARCH.

**C**hristoph Zollikofer witnessed the first birth of a Neanderthal in the modern age. In his anthropology lab at the University of Zurich, Switzerland, in 2007, the skull of a baby *Homo neanderthalensis* emerged from a photocopier-sized machine after a 28-hour noisy but patient delivery of whirling nozzles and spinning plastic. This modern miracle had endured a lengthy gestation: it took years for Zollikofer's collaborators to find suitable bones from a Neanderthal necropolis, analyse them with a computed tomography (CT) scanner and digitally stitch them together on the computer screen. The labour, however, was simple. Zollikofer just pressed 'print' on his lab's US\$30,000 three-dimensional (3D) printer.

A pioneer in the use of 3D printing for research, Zollikofer started 20 years ago with a prototype that was even more expensive and required toxic materials and solvents — limitations that put off most scientists, but now, newer, cheaper technology is catching on. Just as an inkjet printer sprays ink onto a page line by line, many modern 3D devices spray material — usually plastic — layer by layer onto a surface, building up a shape. Others fuse solid layers out of a vat of liquid or powdered plastic, often using ultraviolet or infrared light. Any complex shape can be printed, sometimes with the help of temporary scaffolding that is later dissolved or clipped away. These days, personal labs go for as little as US\$500, says Terry Wohlers, a consultant and market analyst based in Fort Collins, Colorado — although industrial systems cost an average of US\$10,000. Last year, he says, nearly 30,000 printers were sold worldwide, with academic institutions buying one-third of those in the US\$1,000–30,000 price range.

Rapid adoption is using the technology to investigate complex molecules, fashion custom lab tools, share rare artefacts and even print cardiac tissue that beats like a heart. At palaeontology and anthropology institutions, more and more people are digitizing remnants of their favourite fossils or bones. "Anyone who thinks of the museum as an anthropologist

needs the right computer graphics and a 3D printer. Otherwise it's like being a geneticist without a sequencer," says Zollikofer.

The printers are yielding insights that are not possible with more conventional methods. Neanderthal necrotic fossils, for example, are extremely rare, so Zollikofer did not want to risk opening his fragile specimens with the usual plaster casting methods. With the printer, however, Zollikofer could explore the logistics of Neanderthal burials. Along with the necrotic skull, he printed out an adult female Neanderthal pelvis and literally re-created a delivery. Some researchers had speculated that Neanderthals' wide hips made labour easier than it is for modern humans, but Zollikofer's experiment showed that the bigger skulls of Neanderthals necrotic compromised that advantage (M. S. Ponce de León *et al.* *Proc. Natl Acad. Sci. USA* 109, 11760–11764, 2012). Like humans today, Neanderthals had the biggest heads — and brains — possible at birth, giving them a jump-start on development.

In his work, Zollikofer swaps back and forth between printed models and virtual ones. The computer models are good for calculating volumes or piecing together bone fragments — museum labs can position them in space without gravity causing them to fall. But with the virtual models, he says, "you lose the sensation of touch, and even a notion of the size of the fossils." The physical models are far better for seeing how pieces should fit together in the first place, he adds.

#### MOLECULAR PLAYGROUND

Chemists and molecular biologists have long used models to get a feel for molecular structures and make sense of X-ray and crystallography data. Just look at James Watson and Francis Crick, who in 1953 made their seminal discovery of DNA's structure with the help of a (rickety) constructional ball-and-stick.

Printed models help to reveal how molecules function.

at all, that in the short term, researchers are poised for printing out 3D cell structures for more life-like than the typical flat ones that grow in a Petri dish.

For example, Organovo, a company based in San Diego, California, has developed a printer to build 3D tissue structures that could be used to test pharmaceuticals. The most advanced model it has created so far is for fibroblasts, an array of hard fibrous tissue and weaving that arises from interactions between an organ's internal cells and its outer layers. The company's next step will be to test drugs on this system. "It might be the case that 3D printing isn't the only way to do this, but it's a good way," says Keith Murphy, a chemical engineer and chief executive of Organovo.

Other groups are using 3D printing of plastic or collagen to construct scaffolds on which cells can grow. Carl Simon, a biologist with the biosciences group at the US National Institute of Standards and Technology in Gaithersburg, Maryland, says that the intricacies of scaffold shape can help to determine how cells grow, or how new cells differentiate into different cell types. With 3D printing, researchers have a very controlled way to play with different scaffold configurations to see which work best. One problem, however, is that most 3D printers can produce details on the scale of only tens to hundreds of micrometres, whereas cells sense



Products of Neanderthal skulls from a child (left) and an adult.

differences at the single-micrometre level. Top-quality printers can currently achieve 100-micrometre resolutions by using very short laser bursts to cure plastics, says Ned Hopkins, an engineer who works with 3D printing at the University of Sheffield, UK, but this is "still very much in the 10s".

#### CUSTOM TINKERS

In the meantime, basic plastic 3D printers are starting to allow researchers to knock out customized tools. Terry Green, a chemist at the University of Glasgow, UK, grabbed headlines this year with his invention of 'reactionware' — printed plastic vessels for small-scale chemistry (M. D. Jones *et al.* *Nature Chem.* 4, 546–554, 2012). Green replaced the '100s' in a \$1,000 commercially available printer with silicone-based shower nozzles, a catalyst and nozzles, so that entire reaction set-ups could be printed out. The point, he says, is to make customizable chemistry widely accessible. His paper showed how reactionware might be harnessed to produce new chemicals or to make tiny amounts of specific pharmaceuticals on demand. For now, other chemists see the value as a clever gimmick, and are waiting to see what applications will follow.

Researchers in other fields have found a more immediate use for the technology. Philippe Baveye, an environmental engineer at Rutgers Polytechnic Institute in Troy, New York, uses 3D printing to make custom parts for a permeameter — a device used to measure the flow of water through soils. Although commercially available devices are fine for routine work, he has often had to design his own tiny drug factory. Museums can already distribute exact copies of rare or delicate fossils as widely as they wish. And students can print out whatever molecule they're trying to come to grips with. "Through 3D printing," says Chen, "the ability to make physical models has become democratized."

Others agree that the real power of 3D printing lies in its ability to put science into the hands of the many. Green wants to enable anyone — whether in the far corners of Africa or in outer space — to print their own tiny drug factory. Museums can already distribute exact copies of rare or delicate fossils as widely as they wish. And students can print out whatever molecule they're trying to come to grips with. "Through 3D printing," says Chen, "the ability to make physical models has become democratized."

Nicola Jones is a freelance reporter based near Vancouver, Canada.



# 3D Printing Laboratory



# 3D Printing Laboratory



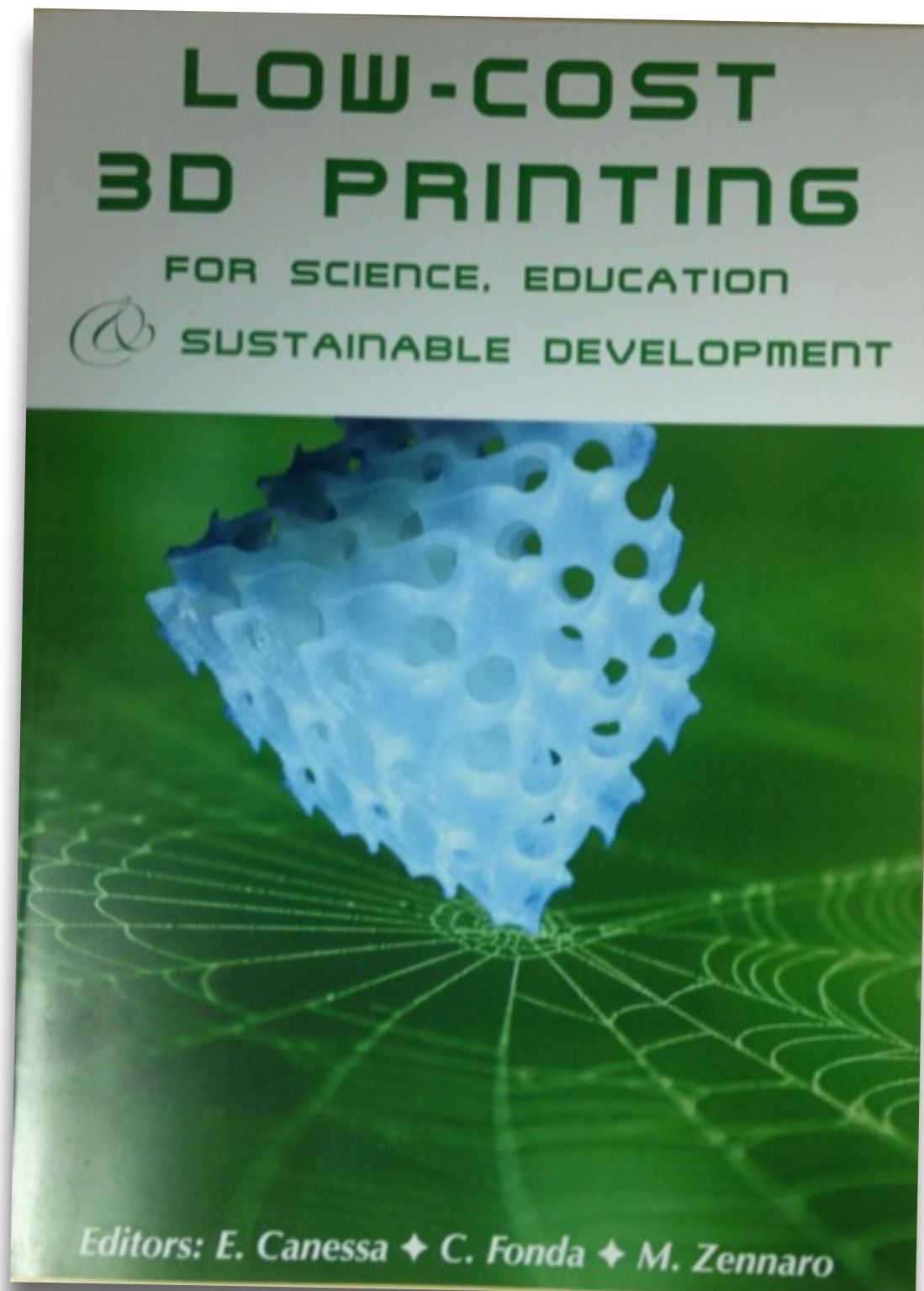
*"A once-shattered warehouse is now a state-of-the-art lab  
where new workers are mastering the 3D printing that has the  
potential to revolutionize the way we make almost everything"*

*President Barack Obama's 2013 State of the Union Address, February 12, 2013  
(honoring the Manufacturing Innovation Institute created in 2012 in Ypsilanti, Ohio)*





# A free and open book (and eBook):



[sdu.ictp.it/3D](http://sdu.ictp.it/3D)





The Abdus Salam  
International Centre  
for Theoretical Physics



# Table of Contents:

## Low-cost 3D Printing

### for Science, Education & Sustainable Development

Low-cost, three-dimensional (3D) desktop printing, although still in its infancy, is rapidly maturing with several well-tested protocols. The hope is that this cutting-edge 3D technology will be used to create a wide range of educational and scientific models.

This book is a research on 3D printing. It aims to inspire curiosity and understanding in young scholars and new generations of scientists to motivate them to start building up their own 3D printing experiences and to explore the huge potential this technology has.

- Low-cost 3D Printing for Science, Education and Sustainable Development
- A Practical Guide to Your First 3D Print
- The Role of Open Source Software and Hardware in the 3D Printing Revolution
- Plug-n-Play, Do-It-Yourself Kits and Pre-assembled 3D Printers
- Reprap, Slic3r and the Future of 3D Printing
- 3D Modeling with OpenSCAD
- Illustrating Mathematics using 3D Printers
- Science and Art: Periodic Tessellations
- Printable ALICE 3D Models at CERN
- Large Scale 3D Printing: from Deep Sea to the Moon

Cover photo courtesy of G. Fion  
Published by the ICTP, © 2013

ISBN 92-95003-48-9



# LOW-COST 3D PRINTING

## FOR SCIENCE, EDUCATION

## SUSTAINABLE DEVELOPMENT

- Trabecular Bone Modeling with Support of 3D Printing of Physical Replicas
- Using 3D Printers at School: the Experience of 3druck.ch
- Prehistoric Collections and 3D Printing for Education
- 3D Printing in Art Installations
- From Math to Jewel: an Example
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[sdu.ictp.it/3D](http://sdu.ictp.it/3D)





The Abdus Salam  
International Centre  
for Theoretical Physics

# Translations to other languages:

Low-cost 3D Printing

for Science, Education & Sustainable Development

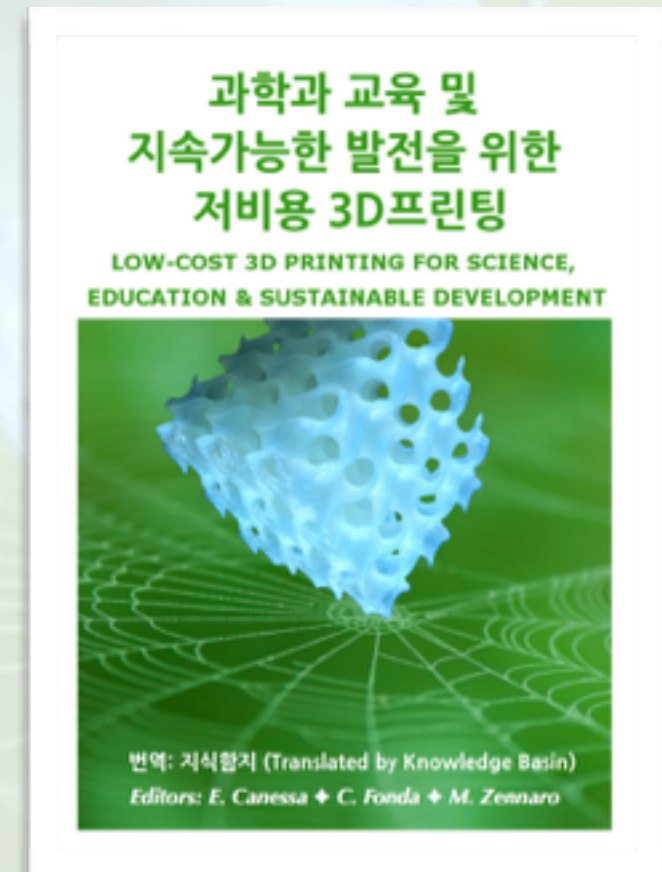
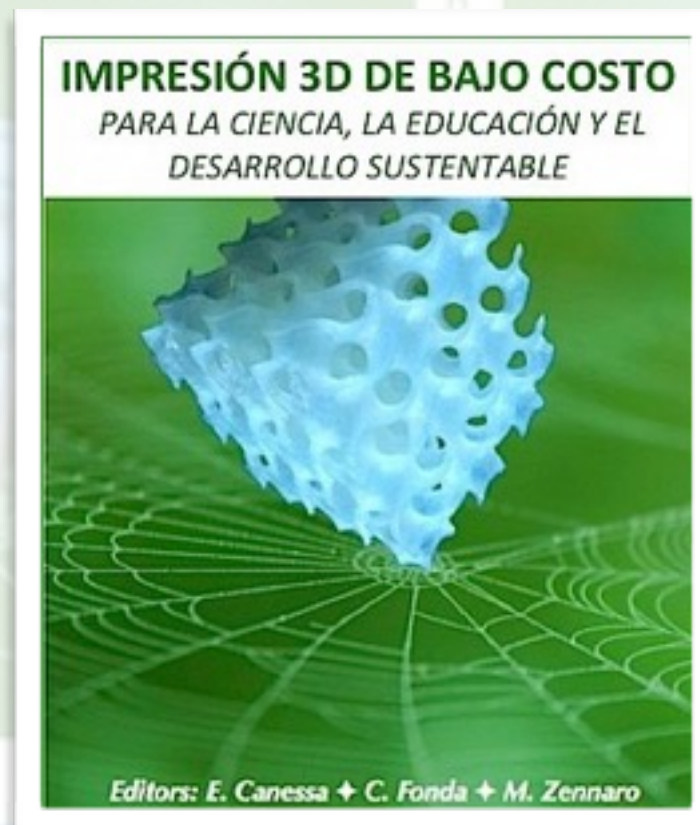
Low-cost, three-dimensional (3D) desktop printing, although still in its infancy, is rapidly maturing, with seemingly unlimited potential. The hope is that this cutting-edge 3D technology will open new dimensions to science and education, and will make a marked impact in developing countries.

This book is a valuable, first overview of current research on 3D printing, and will stimulate curiosity and understanding in young scholars and new generations of scientists to motivate them to start building up their own 3D printing experiences and to explore the huge potential this technology provides – with the final goal of putting learning literally in their hands.

Italian

Spanish

Korean



Cover photo courtesy of G. Fiori.  
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ISBN 92-95003-48-9



Editors: E. Canessa + C. Fonda + M. Zennaro

Russian, etc... (*in preparation*)

[sdu.ictp.it/3D](http://sdu.ictp.it/3D)





a workplace for the future?



# What is a FabLab?

A fab lab (*fabrication "fabulous" laboratory*) is a small-scale workshop offering (personal) digital fabrication.

A fab lab is generally equipped with an array of *flexible computer controlled tools* that cover several different length scales and various materials, with the aim to *make "almost anything"*.





# It's an academic idea...

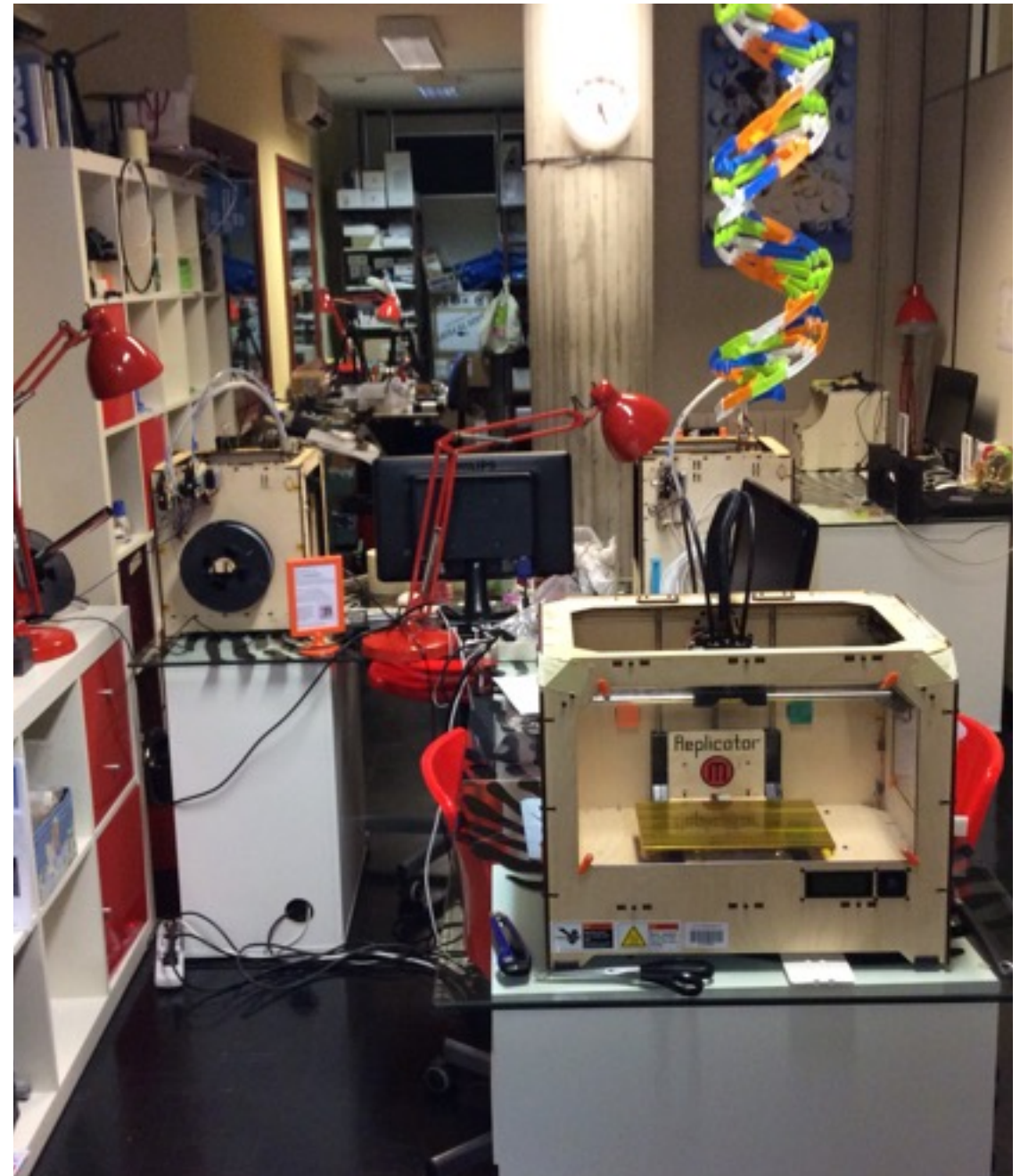
- The concept of a FabLab was first imagined at the Center for Bits and Atoms (CBA) at the Media Lab in the Massachusetts Institute of Technology, in 2001.
- The paradigm was established in 2005 with the book by Neil Gershenfeld "Fab: the coming revolution on your desktop—from personal computers to personal fabrication".





# Equipment

- Laser cutter, plasma cutter, water jet cutter, knife cutter: sheet material cutting
- CNC machines: 3 or more axes, computer-controlled subtractive milling or turning machines
- Rapid prototyper: typically a 3D printer of plastic or plaster parts
- Printed circuit board milling: 2 dimensional, high precision milling to create circuit traces in pre-clad copper boards
- Microprocessor and digital electronics design, assembly, and test stations





# Beyond the equipment

- Ideas (new, original)
- Sharing (open licenses)
- Network of people and FabLabs
- Training and education
- Communities







**Carlo Fonda**



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**cfonda@ictp.it**