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

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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 Imeperial College in London, is on the right. Paolo Budinich, the chief organizer of the seminar, is to his immediate right.

ICTP

UNESCO
United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

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

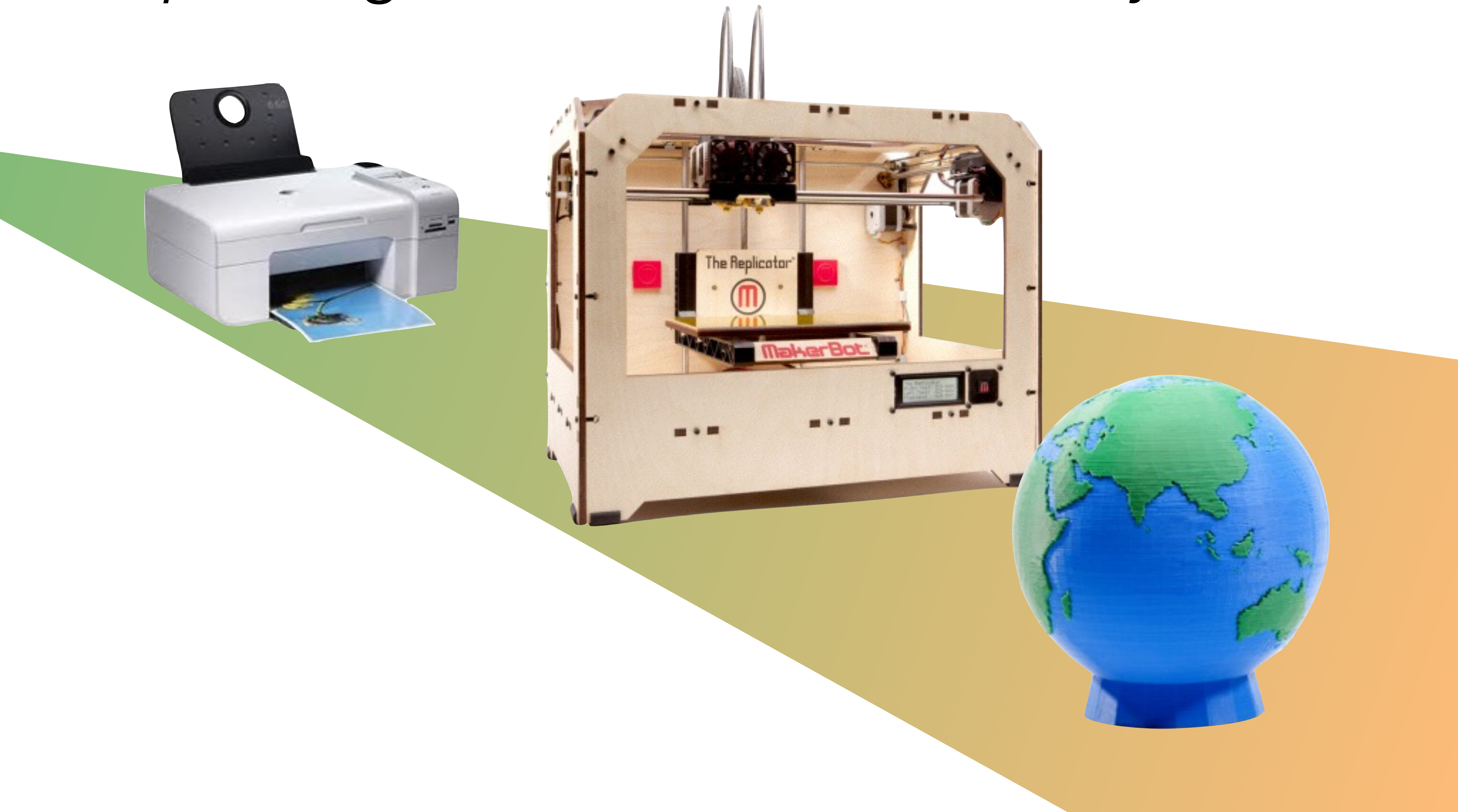
- 60% from Developing Countries
- 40% from Developed Countries

Agenda of this Workshop

- 30' *Demo*: how to generate 3D objects with OpenSCAD language
- 30' *Demo*: other tools: webapps, K3DSurf, Mathematica™
- 120' Introduction to low-cost 3D printing: how-to & *demo* 30'
- 30' Case studies:
  - replicating IMAGINARY models using low-cost 3D printers
  - getting math objects from *Thingiverse* and other websites
- Discussion

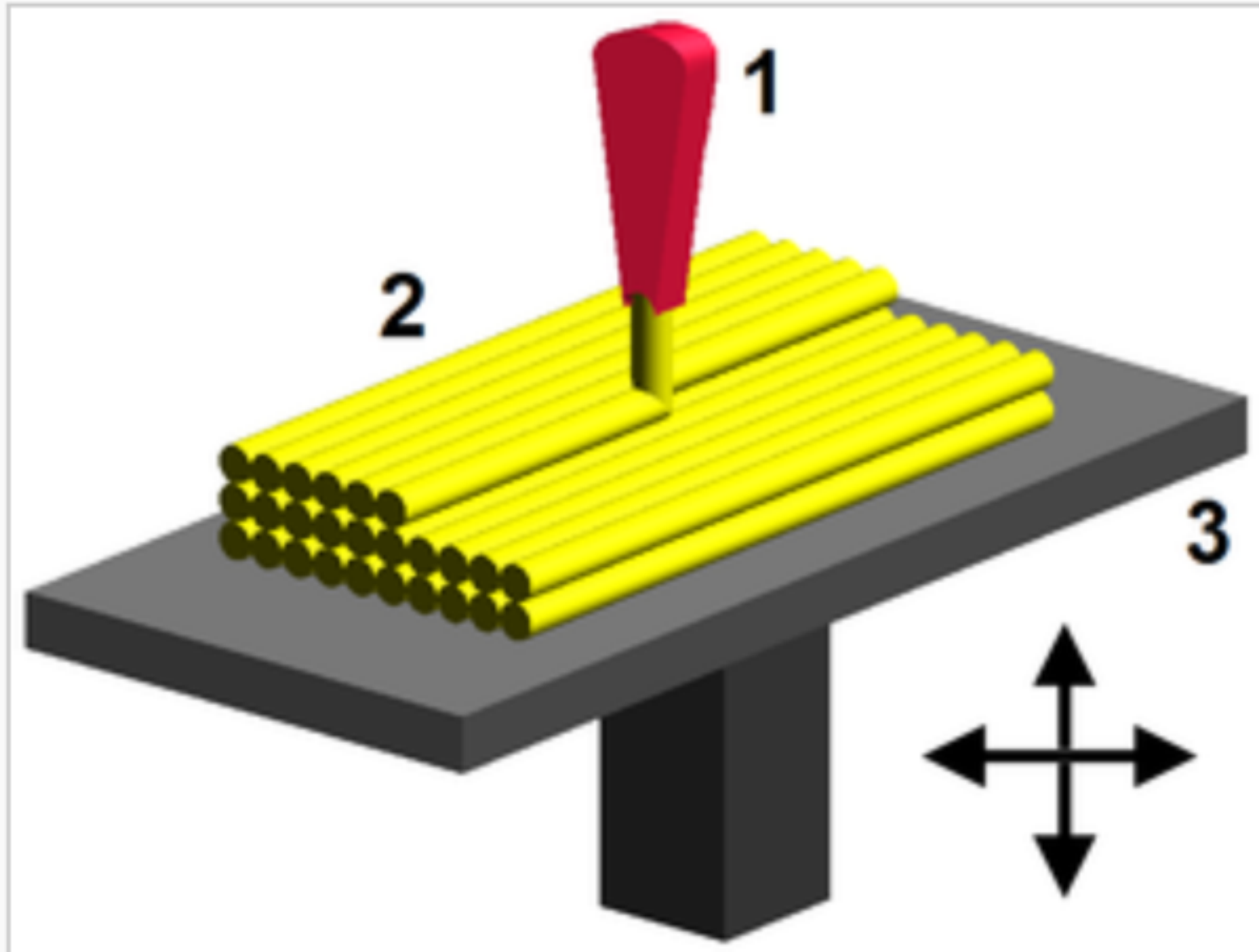
Intro to low-cost 3D printers

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$+)

- 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 ;-)

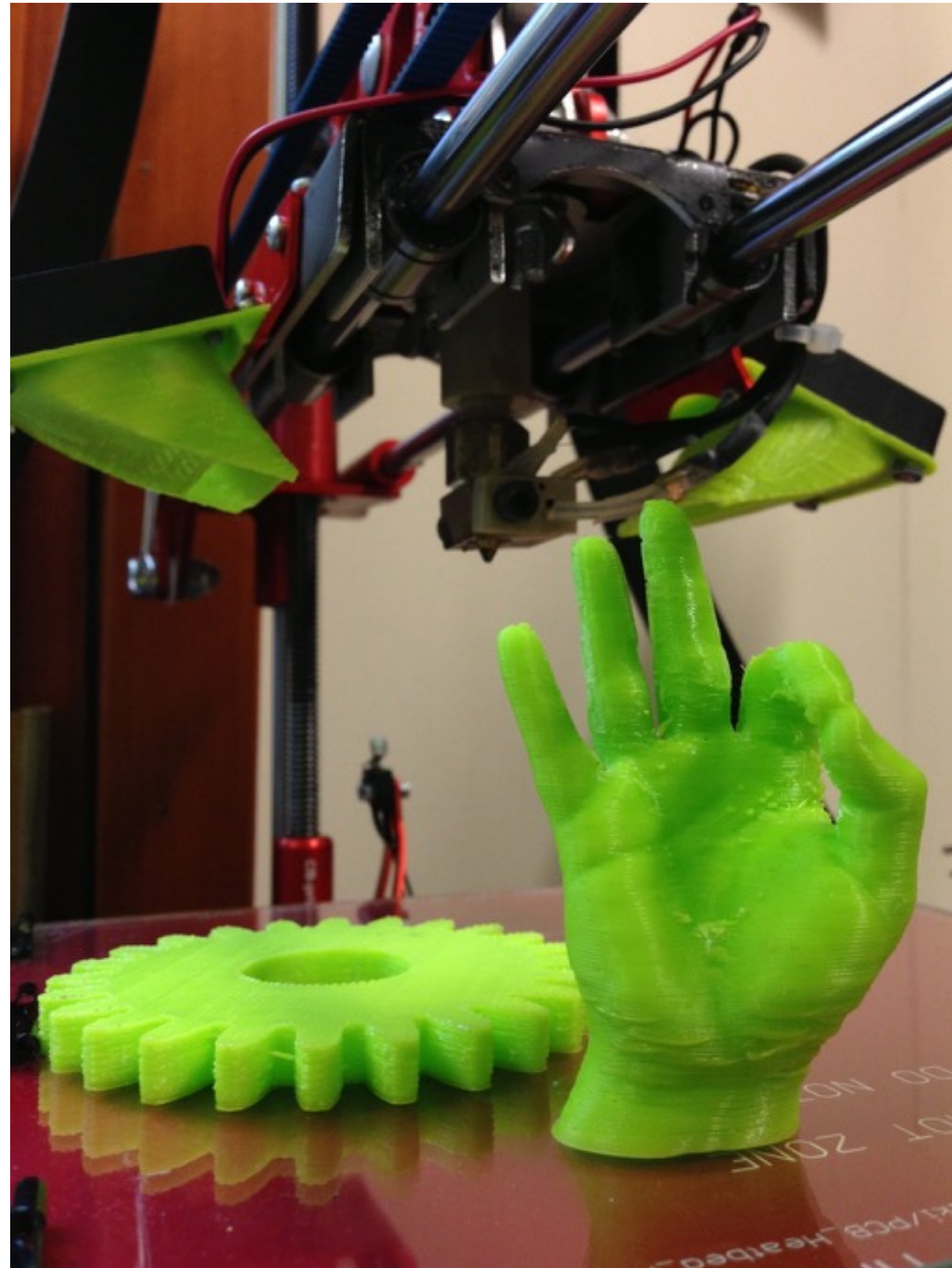


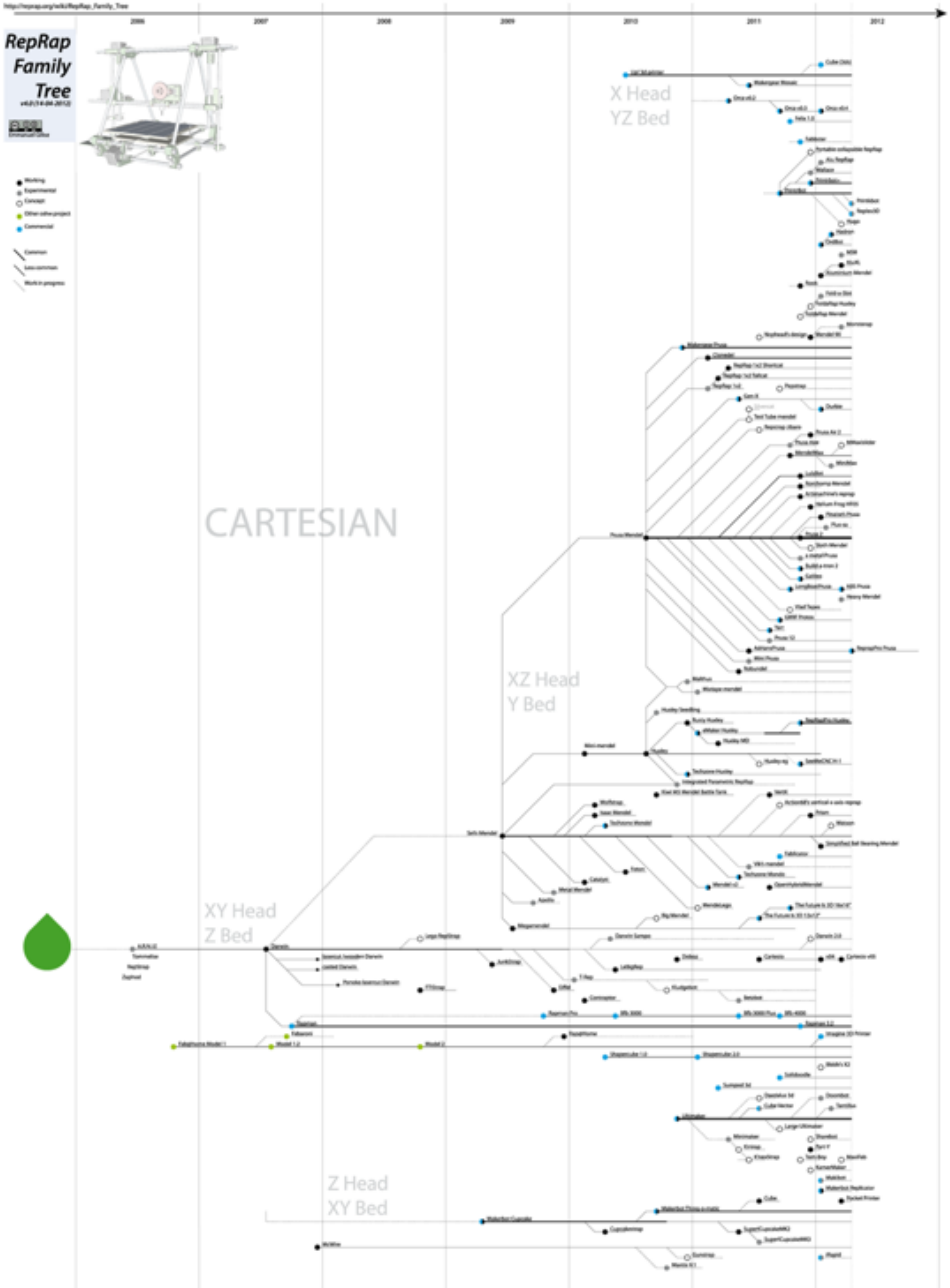
Low-cost *personal*
3D printers

cost: from 300 to 3000 USD

Open source + Open Hardware

- 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





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

Cartesian Coordinates

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

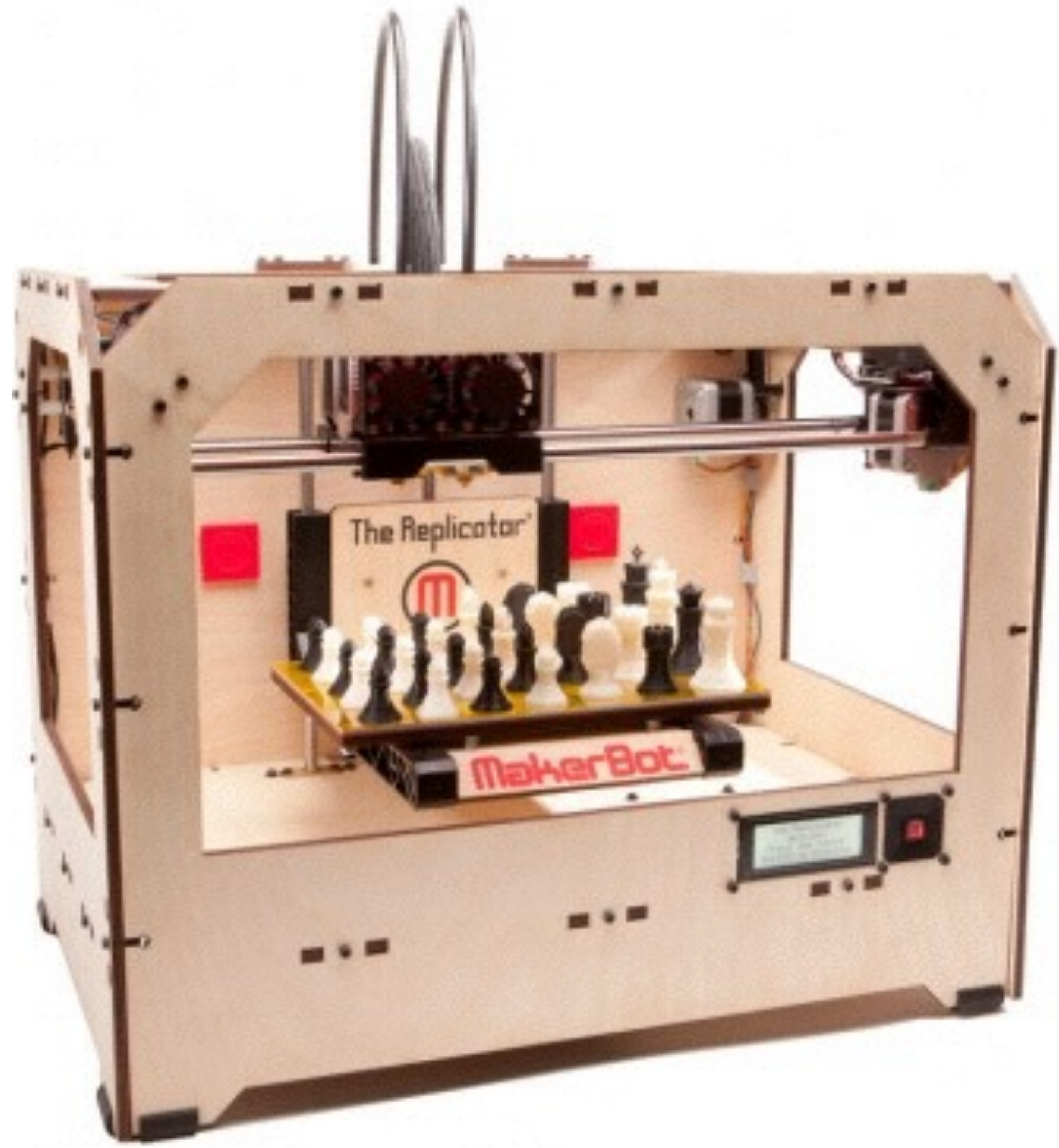
http://www.thingiverse.com/thing:2064

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!

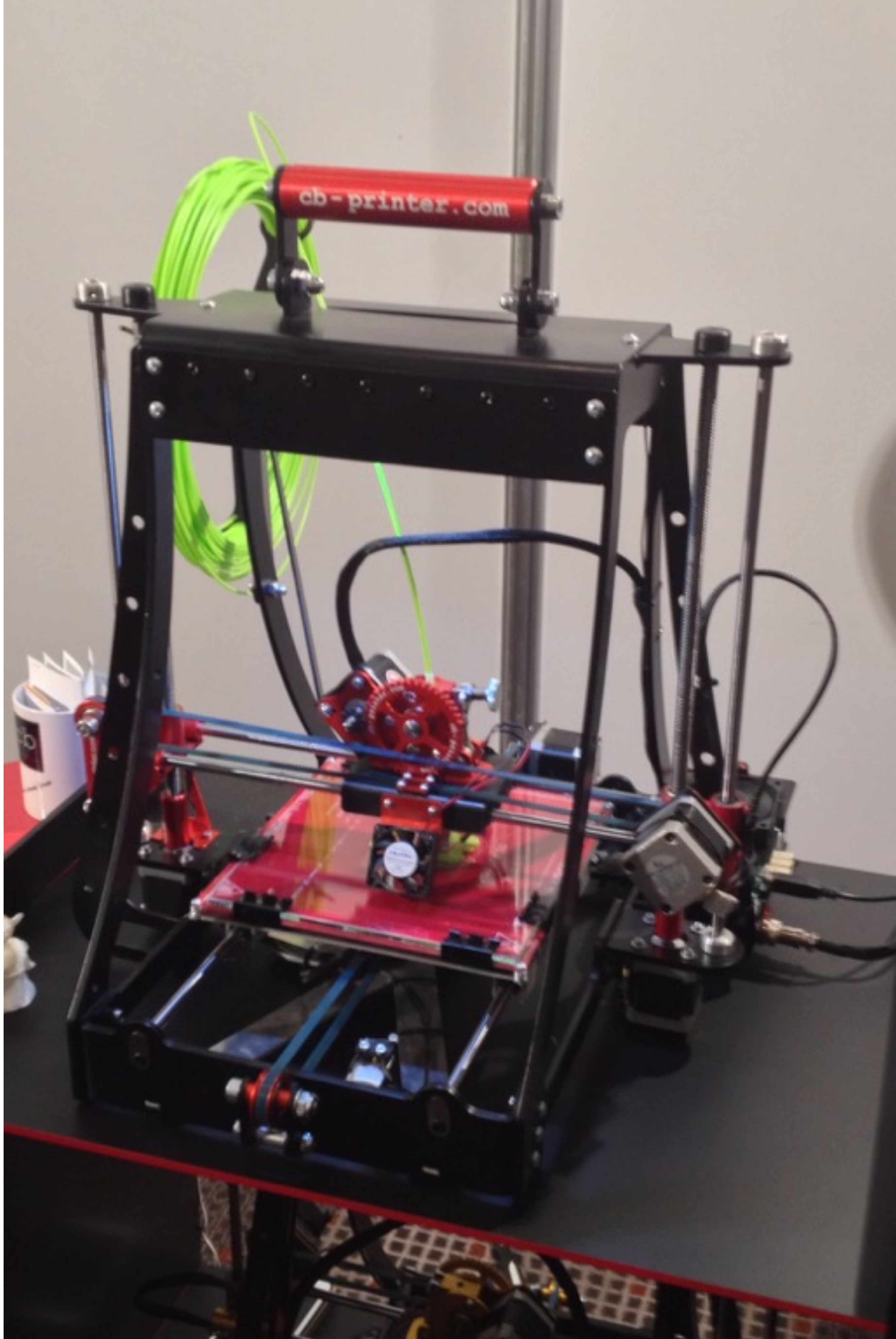
Makerbot Replicator

- 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)



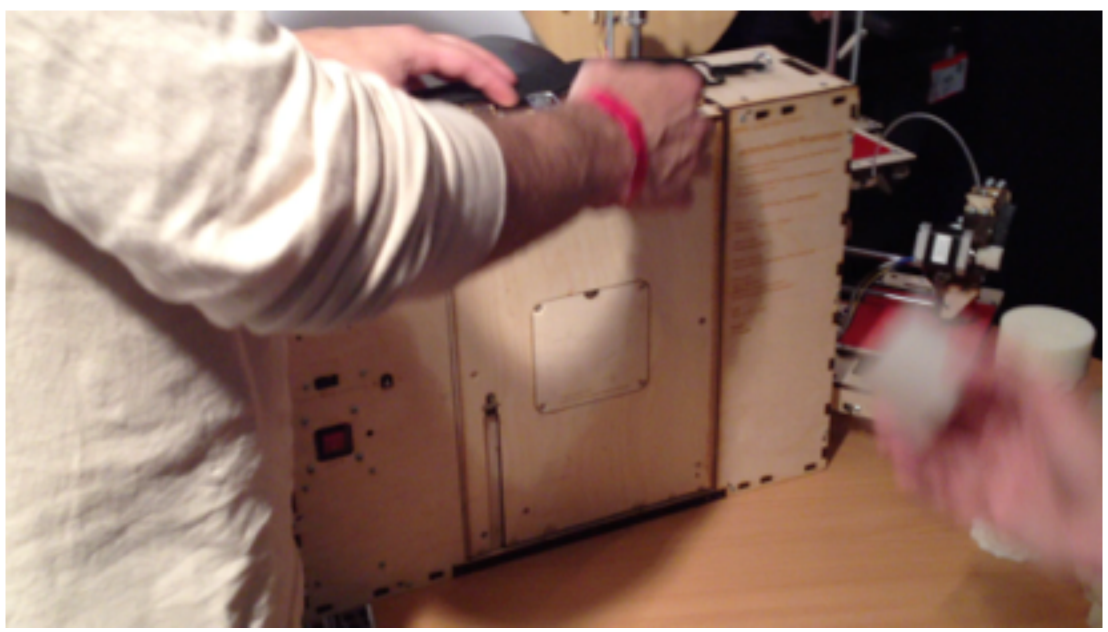
RepRap: Prusa/Mendel/Darwin/etc...

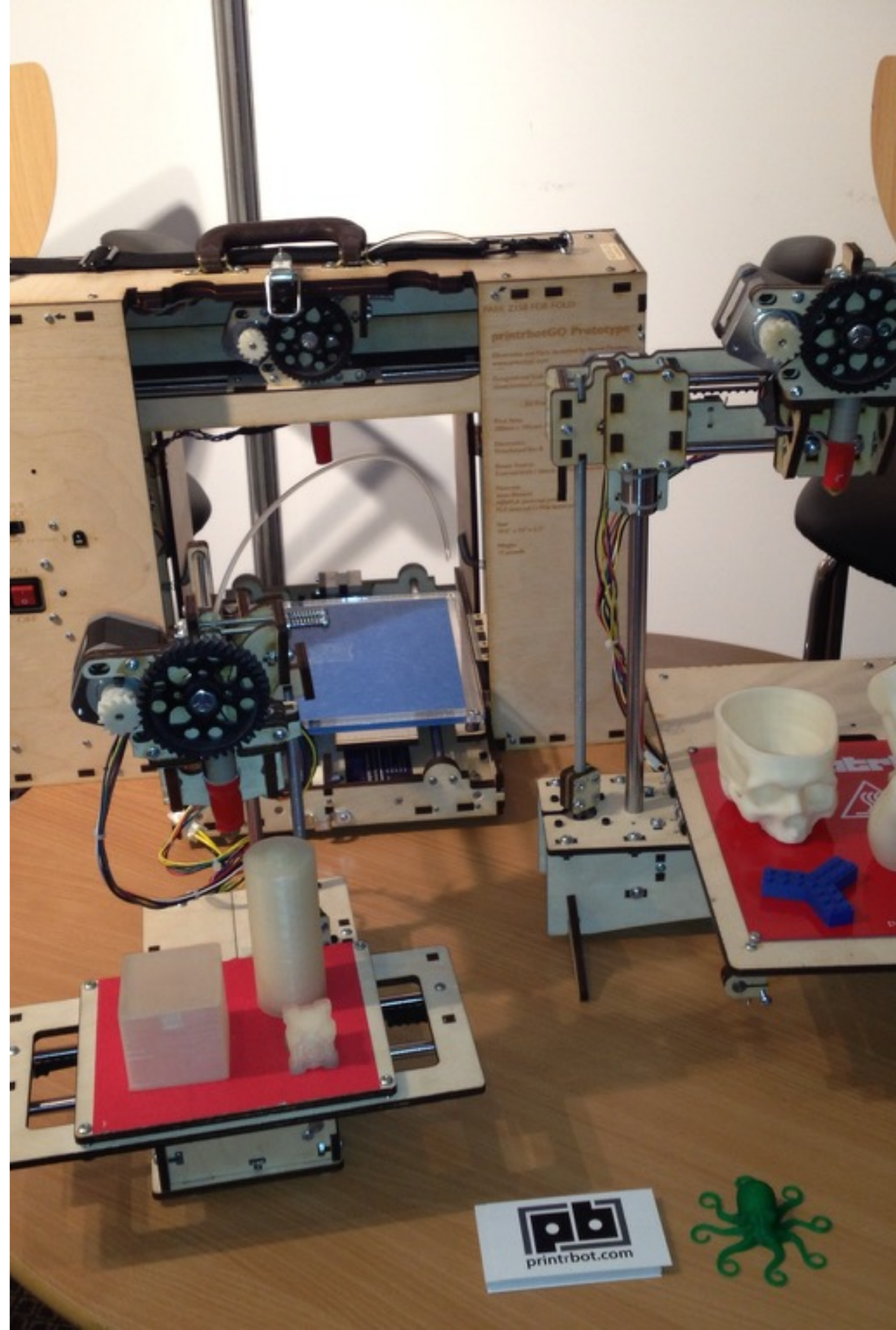
- Many variations on the theme
- Mostly designed (and marketed) by members of the hacker community in US and Europe
- Everything is open, you can buy or build/modify them



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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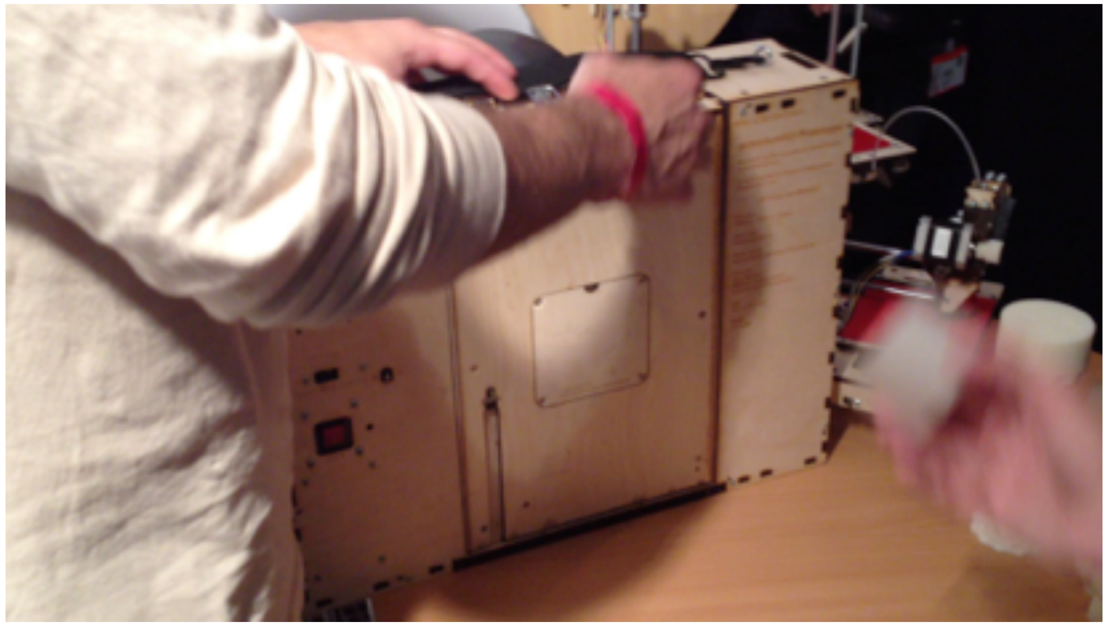
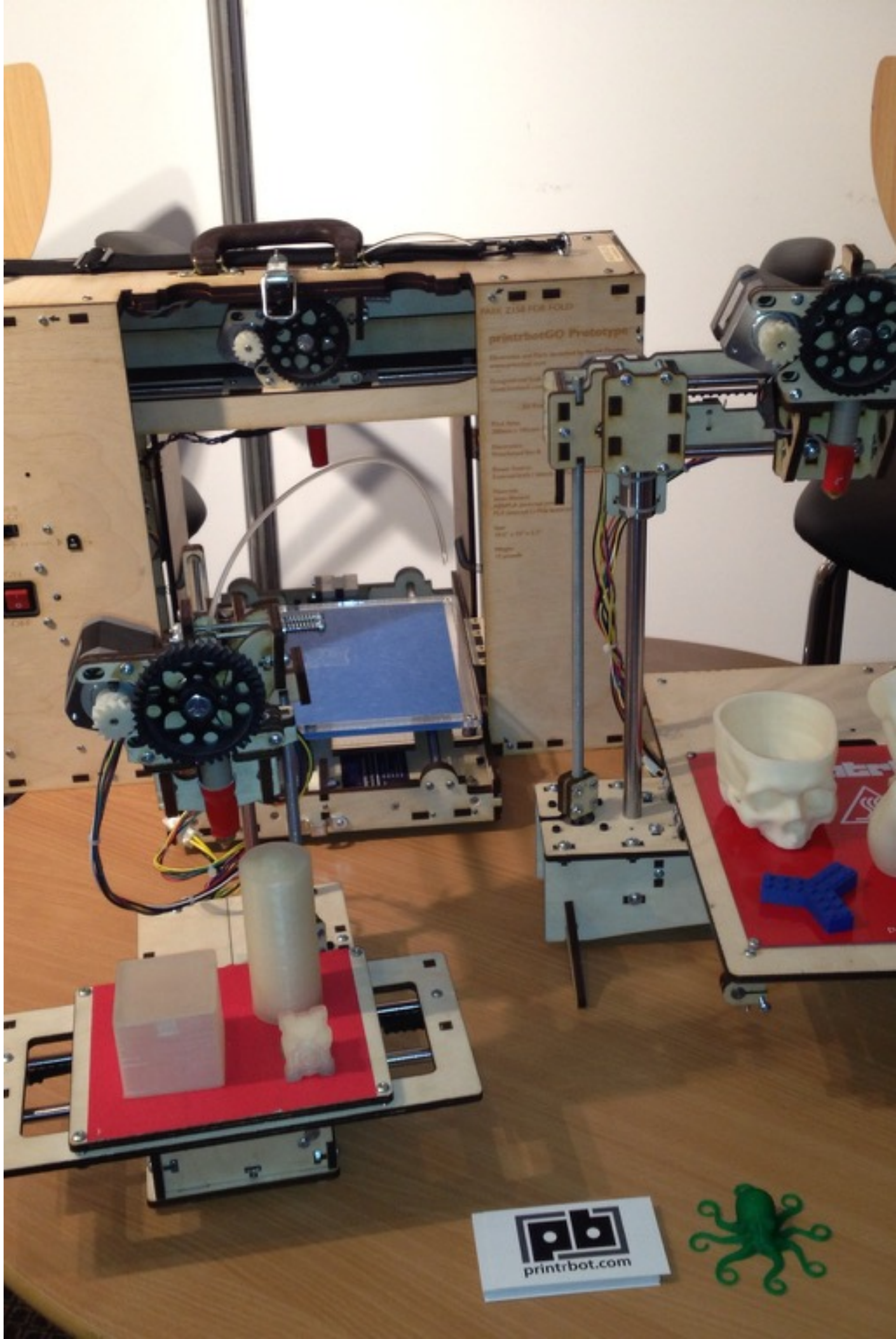
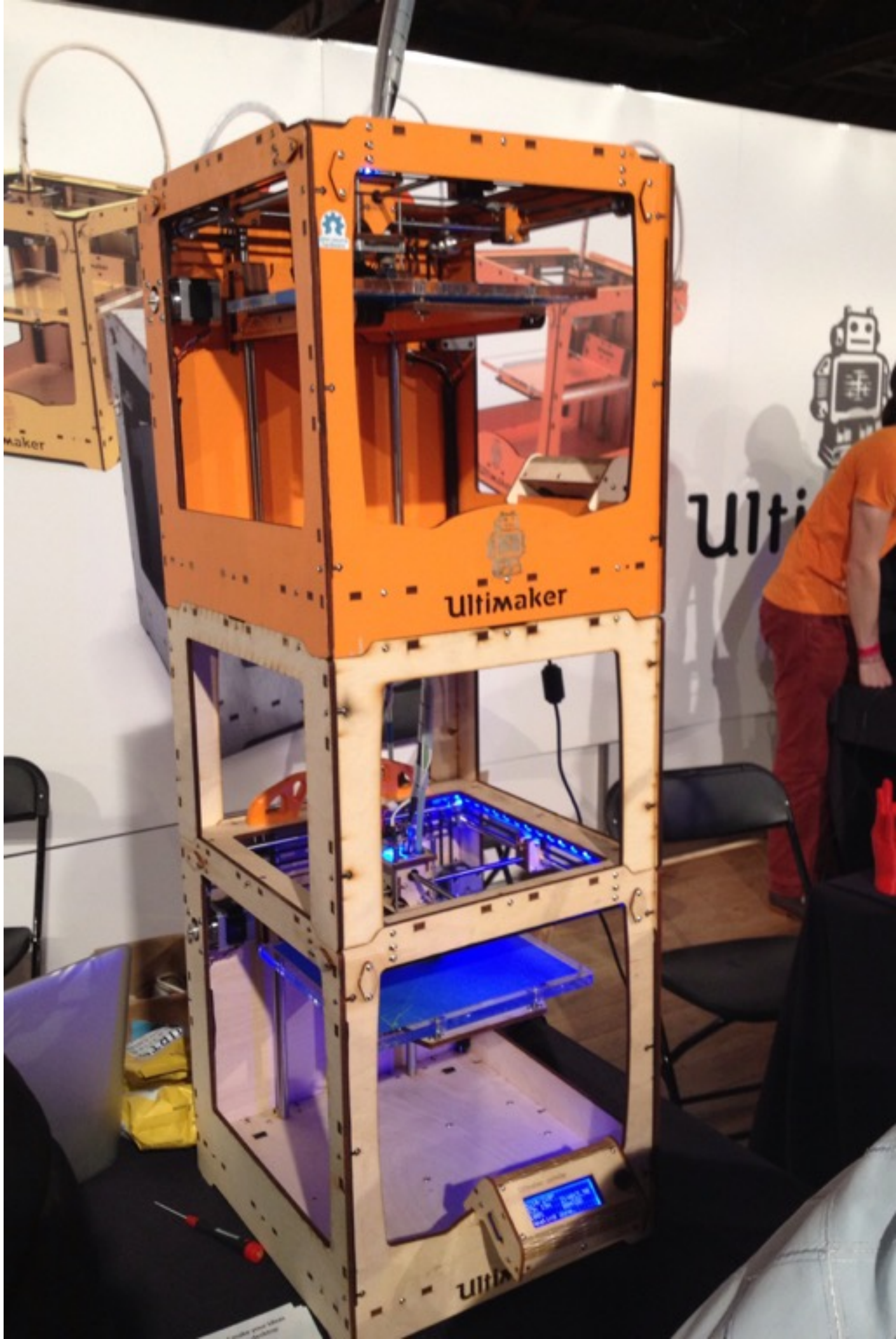




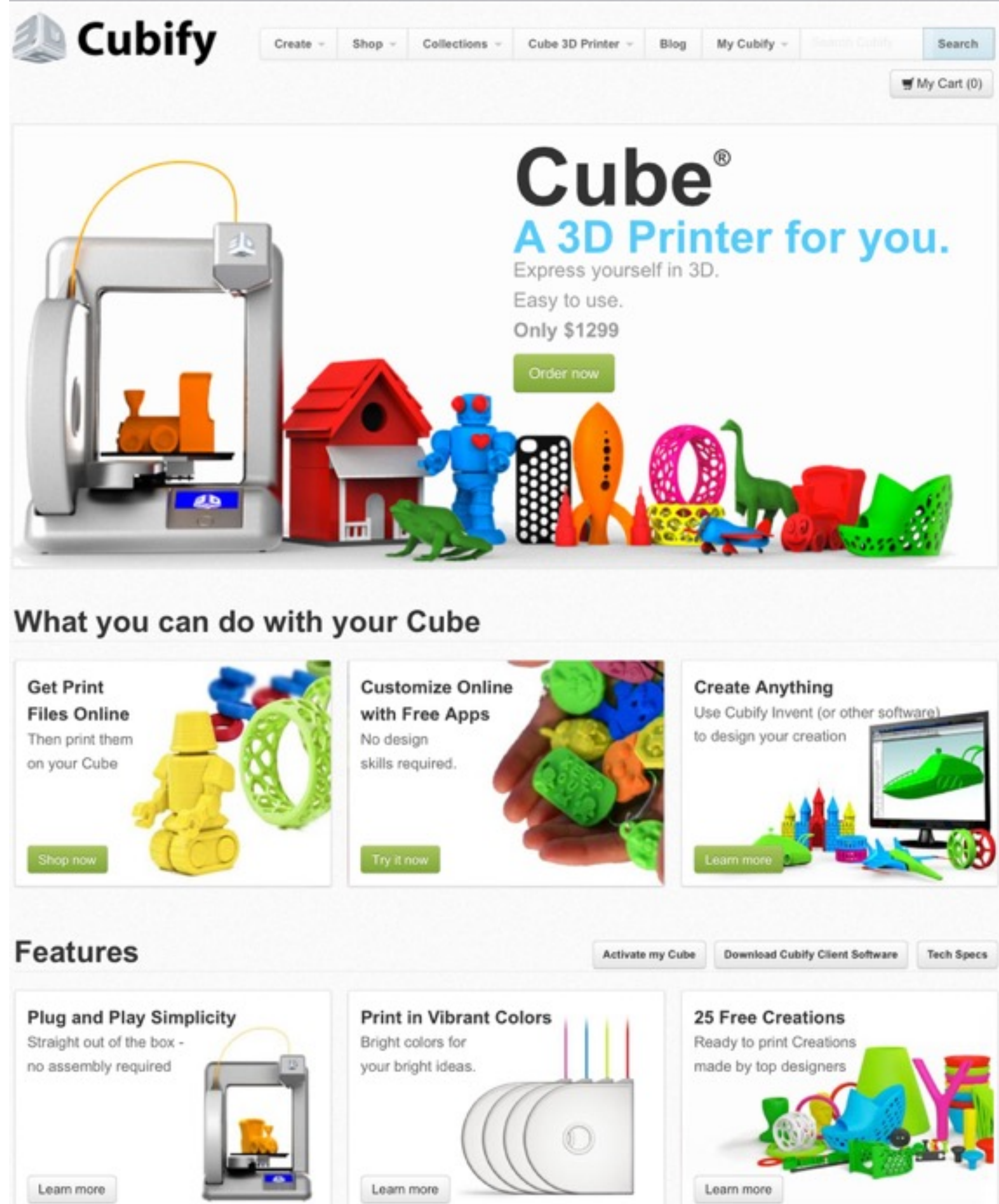
Not only from U.S.: the Ultimaker

- 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)

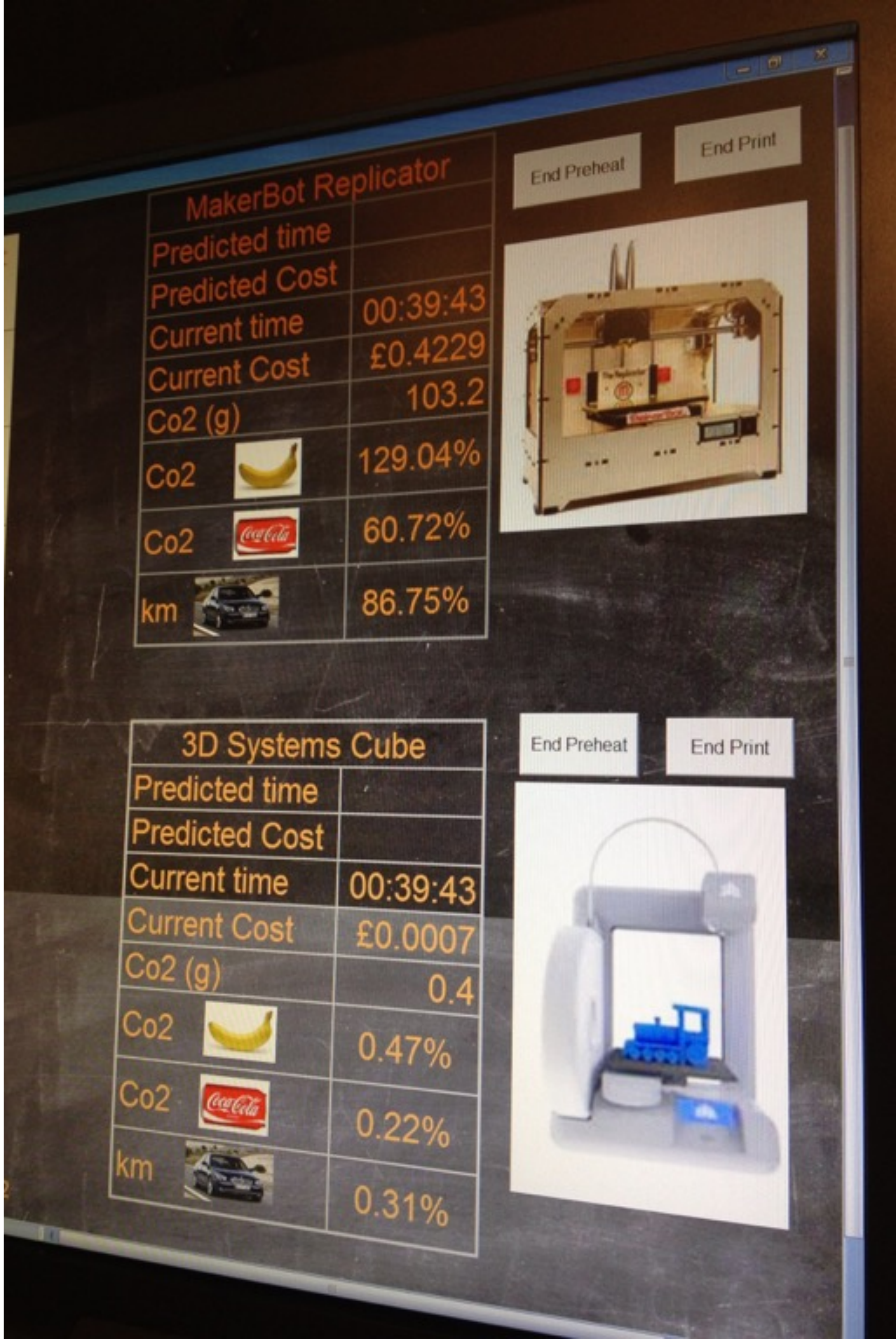


The Cube ($1299)

The Cube ($1299)

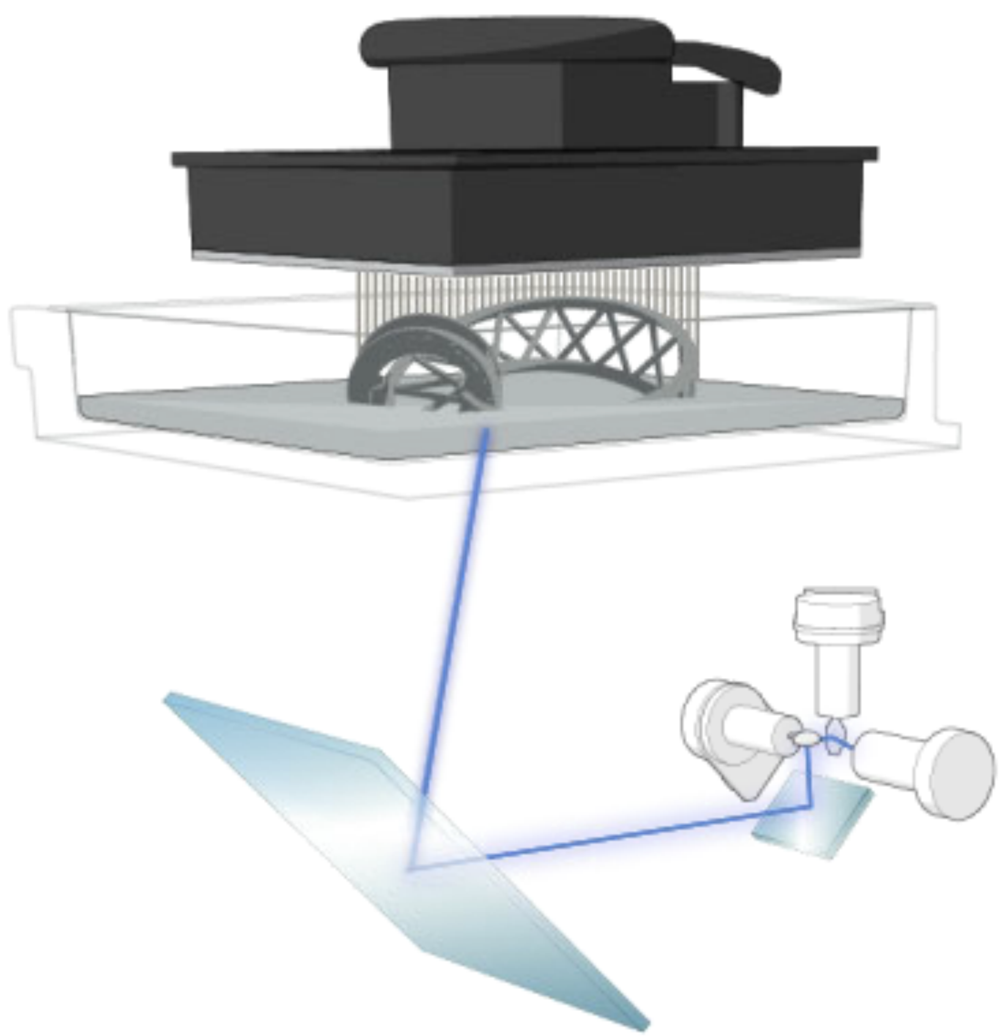
And many more...

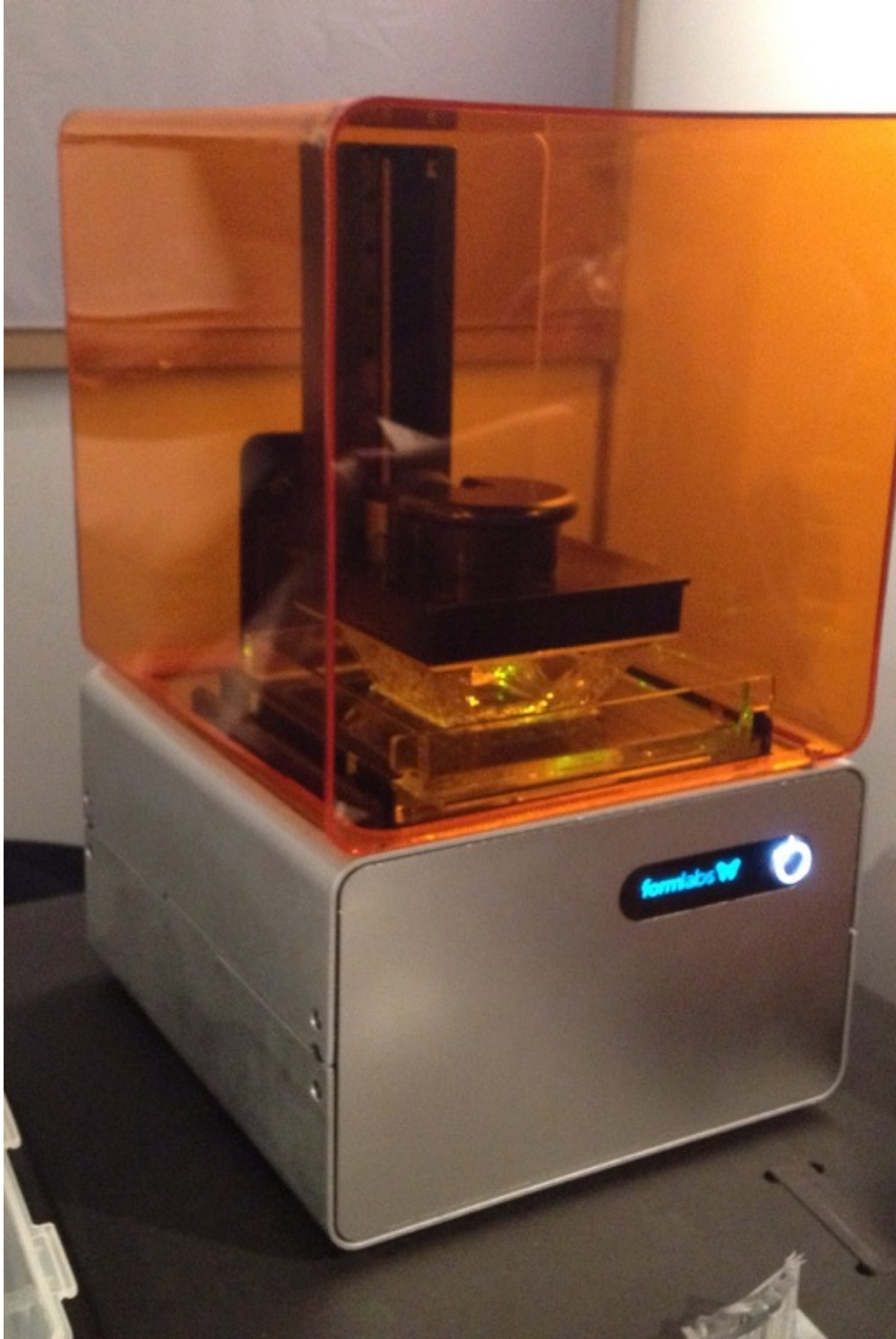
- Different solutions
- Different level of skills required to operate
- Different prices
- Different philosophies
- The market is still growing quickly and searching an equilibrium...



Laser + liquid resin

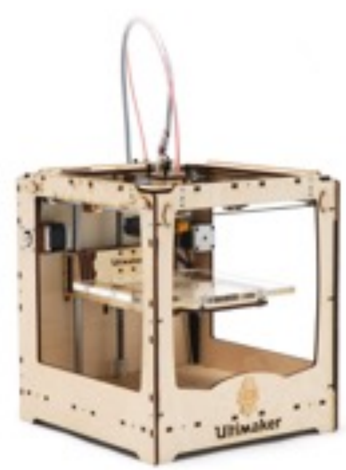
- another promising technology from low-cost 3D printers: it uses a special liquid resin that costs 3x more than plastic, has better resolution and precision.





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

Pro only ➡ first personal (for hackers) ➡ really personal (mass produced)



? **???**

HOW to print an object?

...practical 3D-printing for beginners

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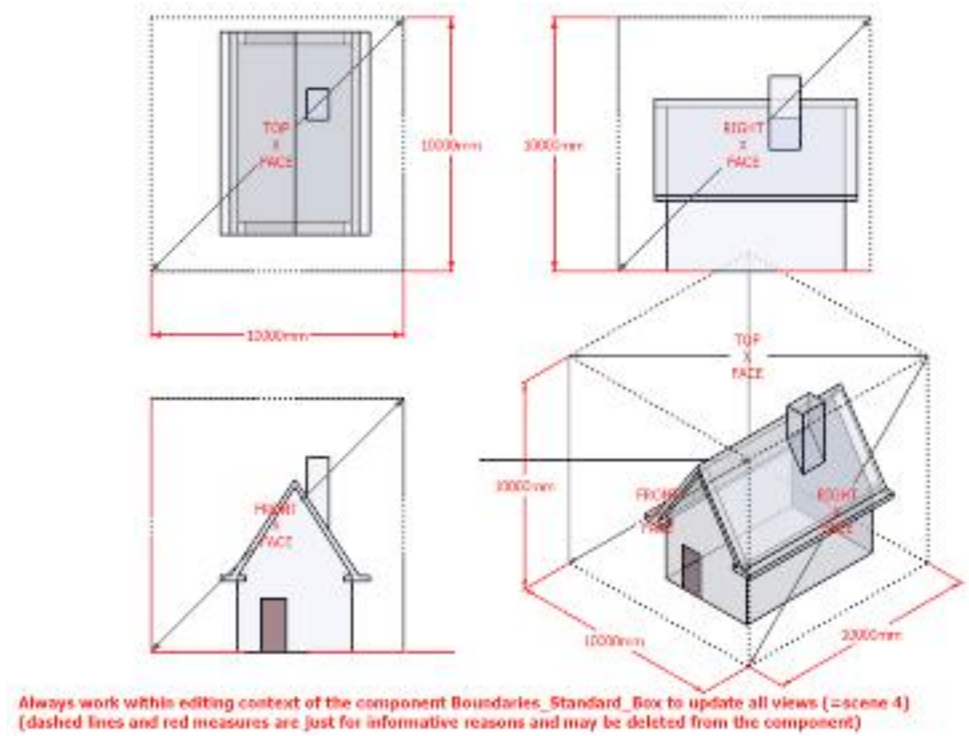
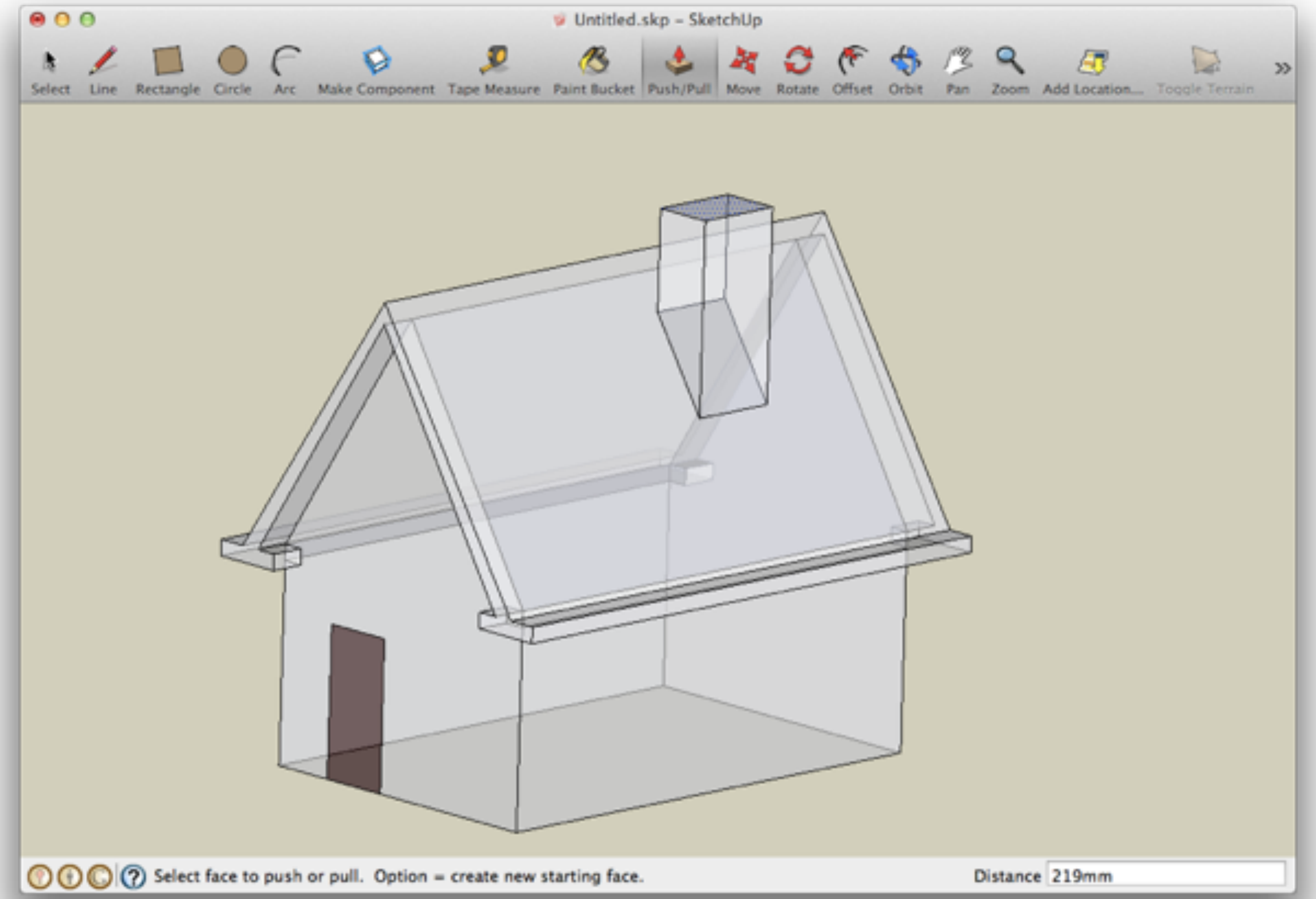
...practical 3D-printing for beginners

#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...



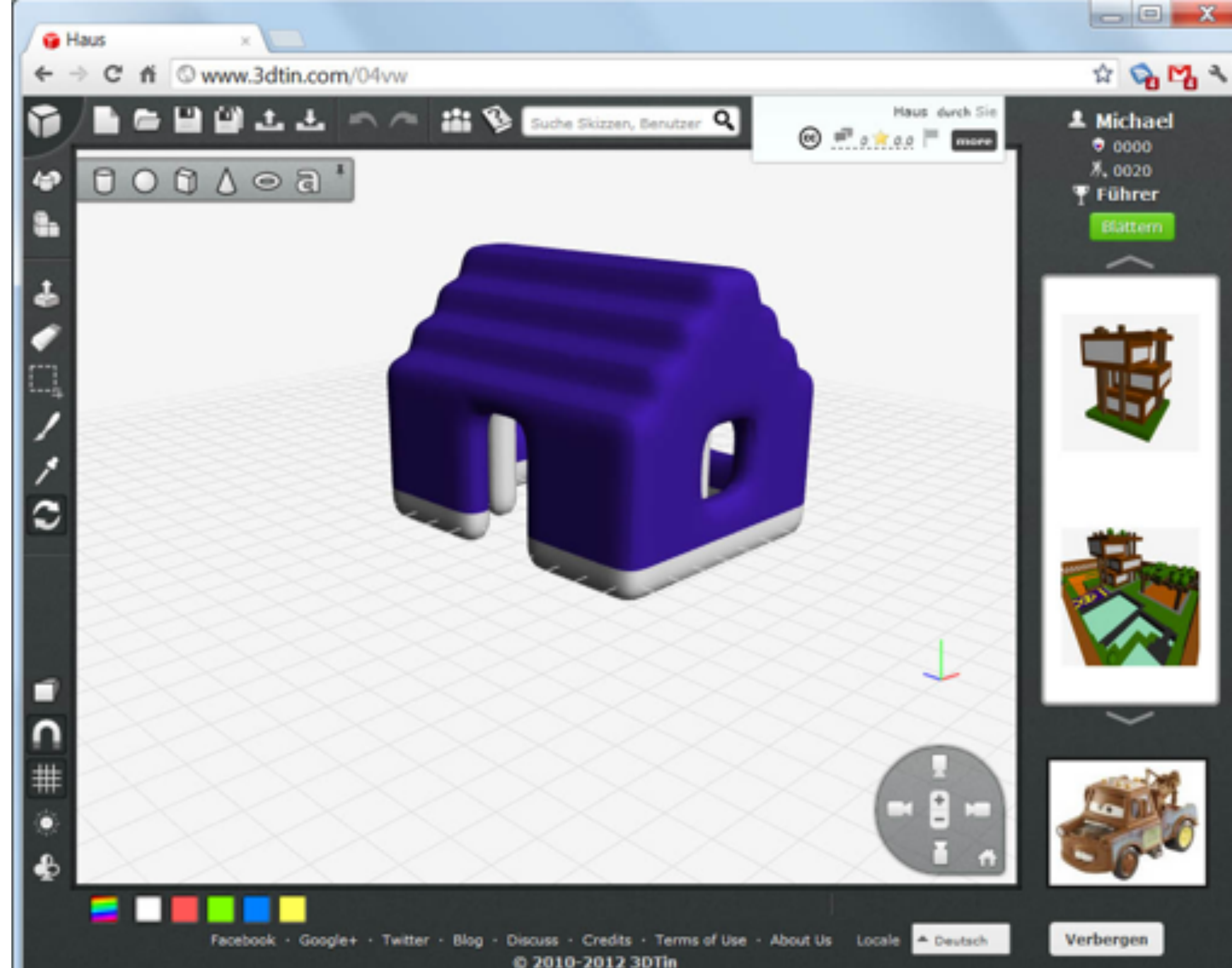


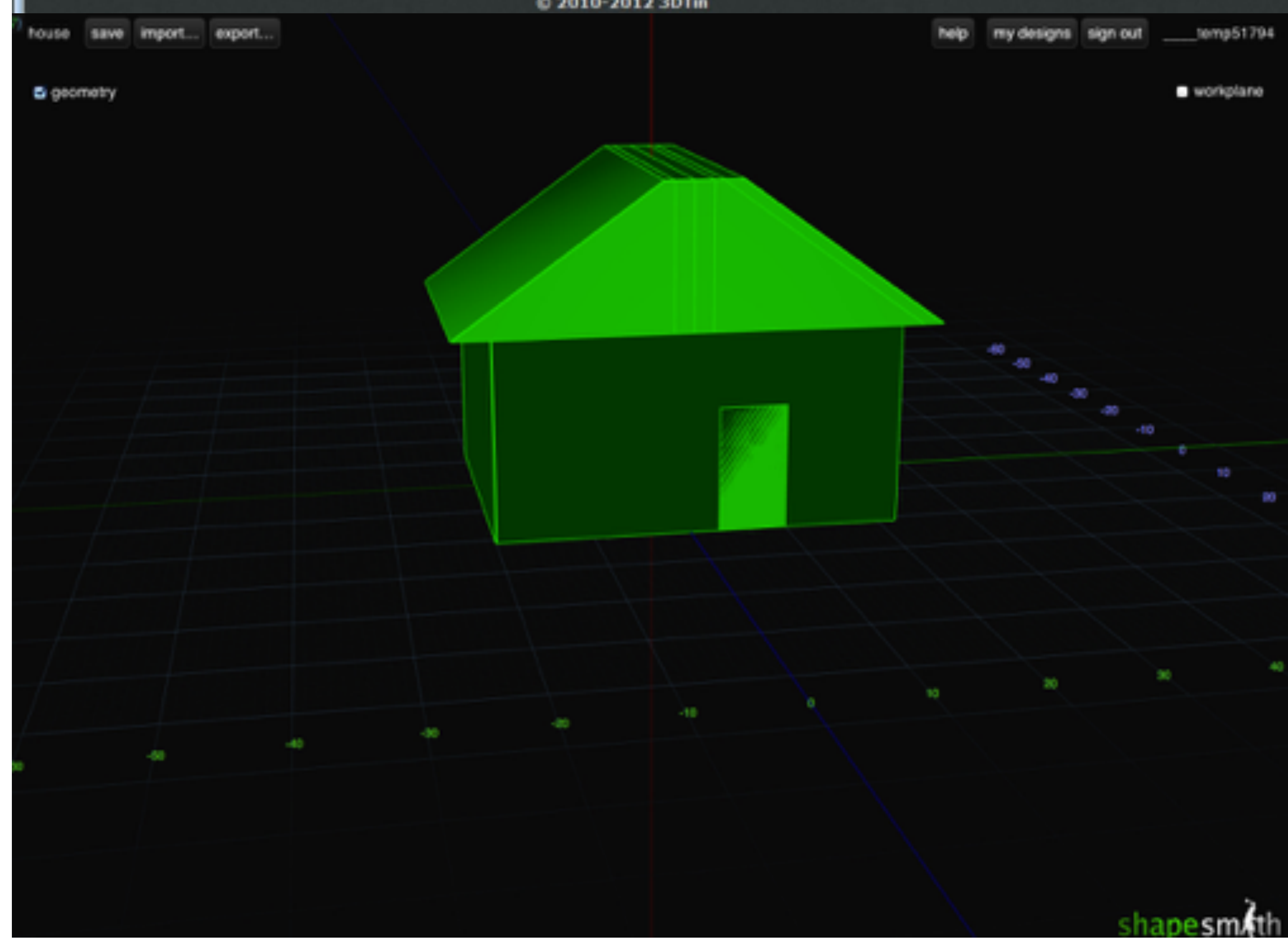
Program VS WebApp

- 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

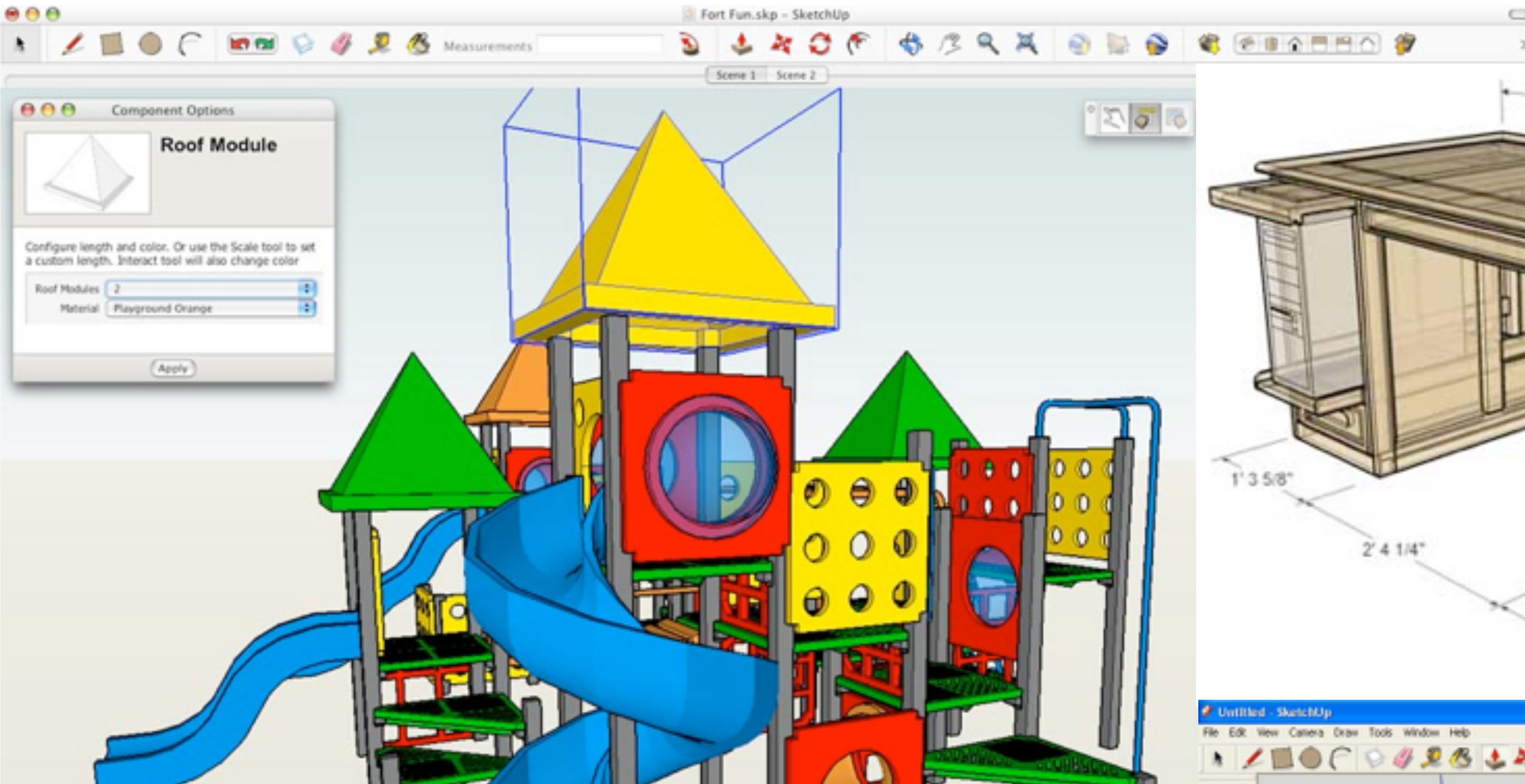


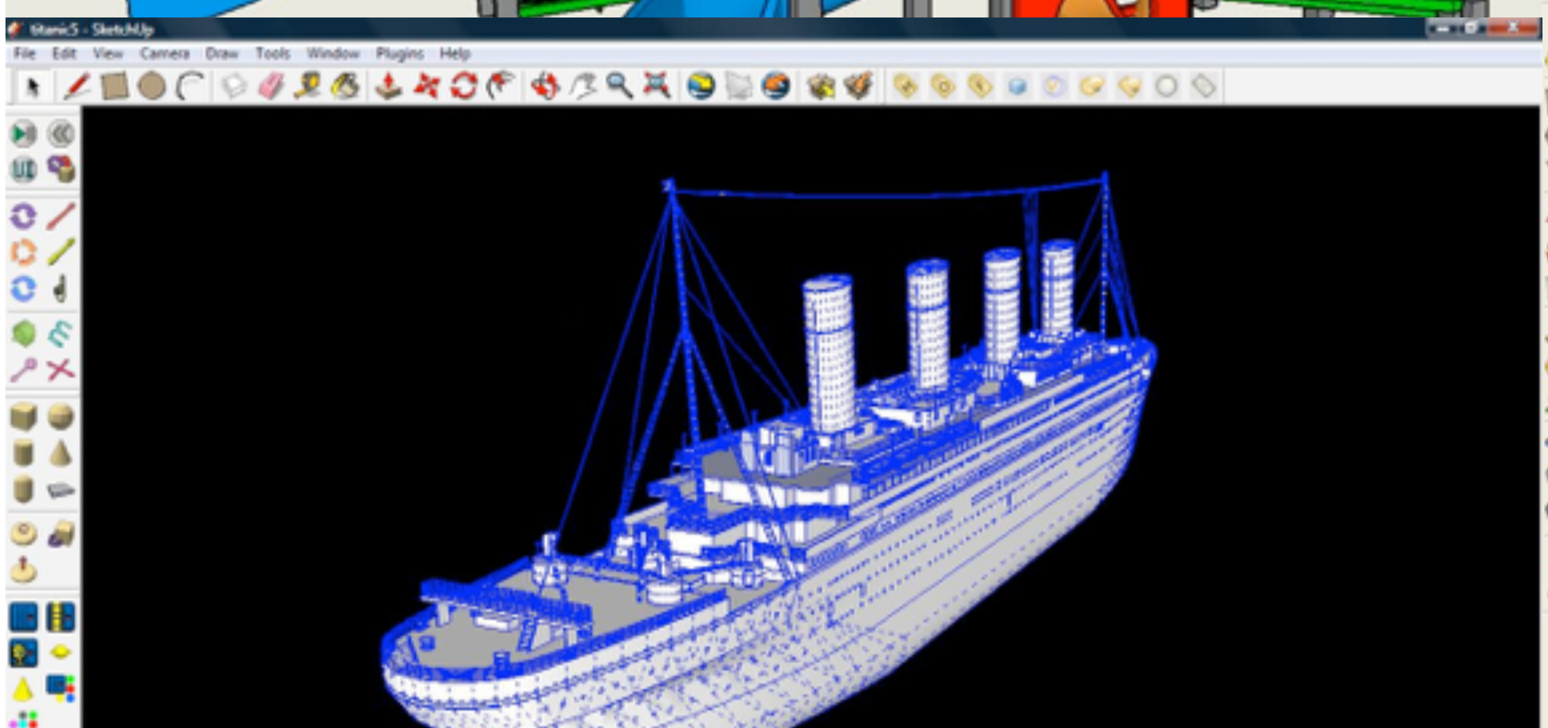


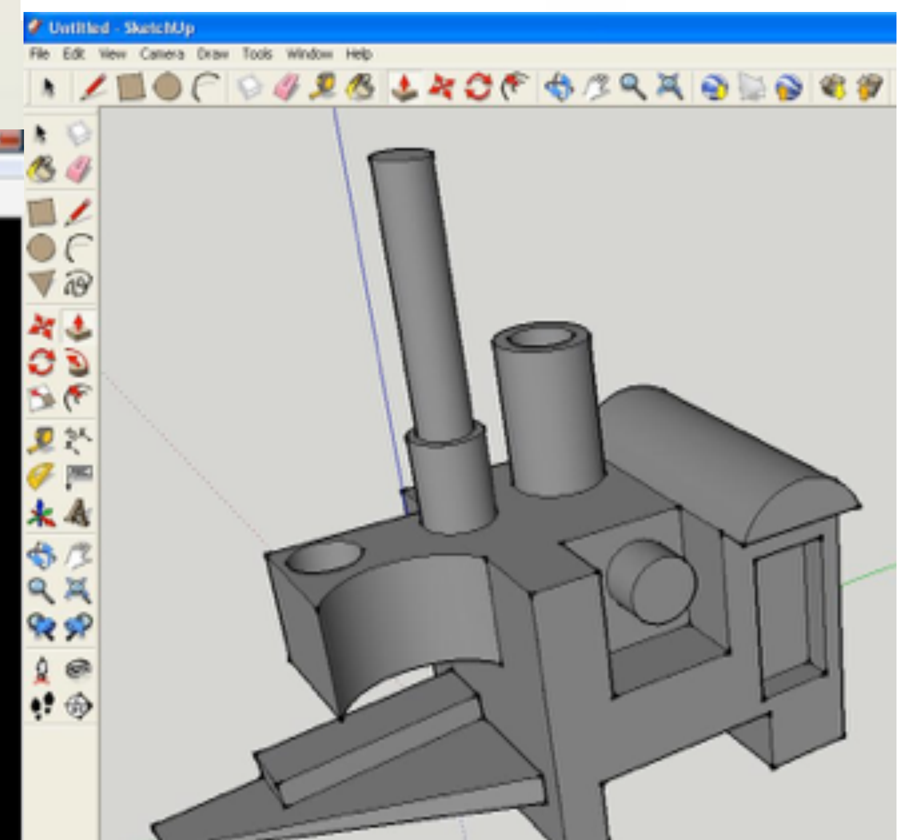
Examples: *free* software for *technical* 3D modeling

- 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

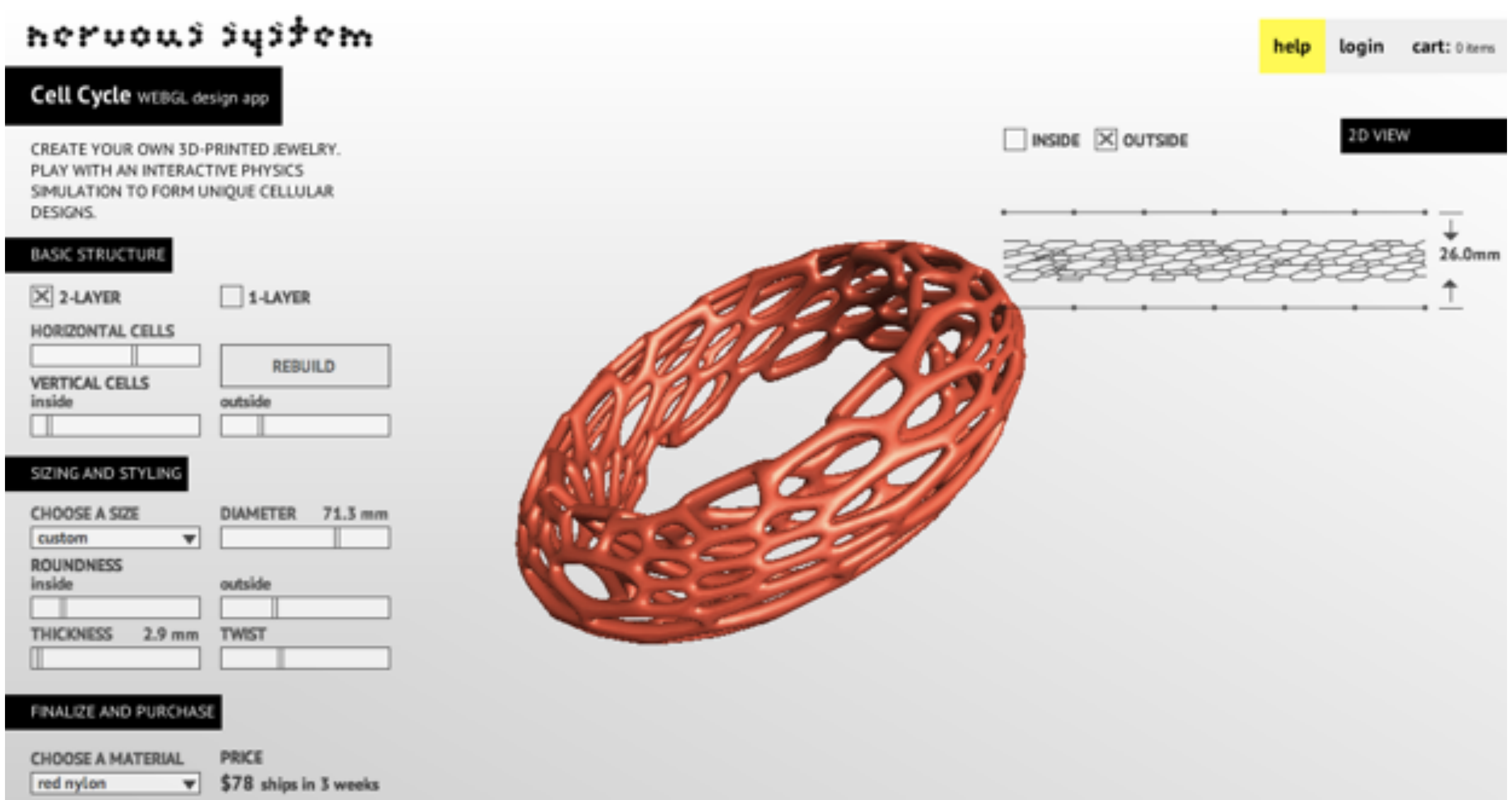


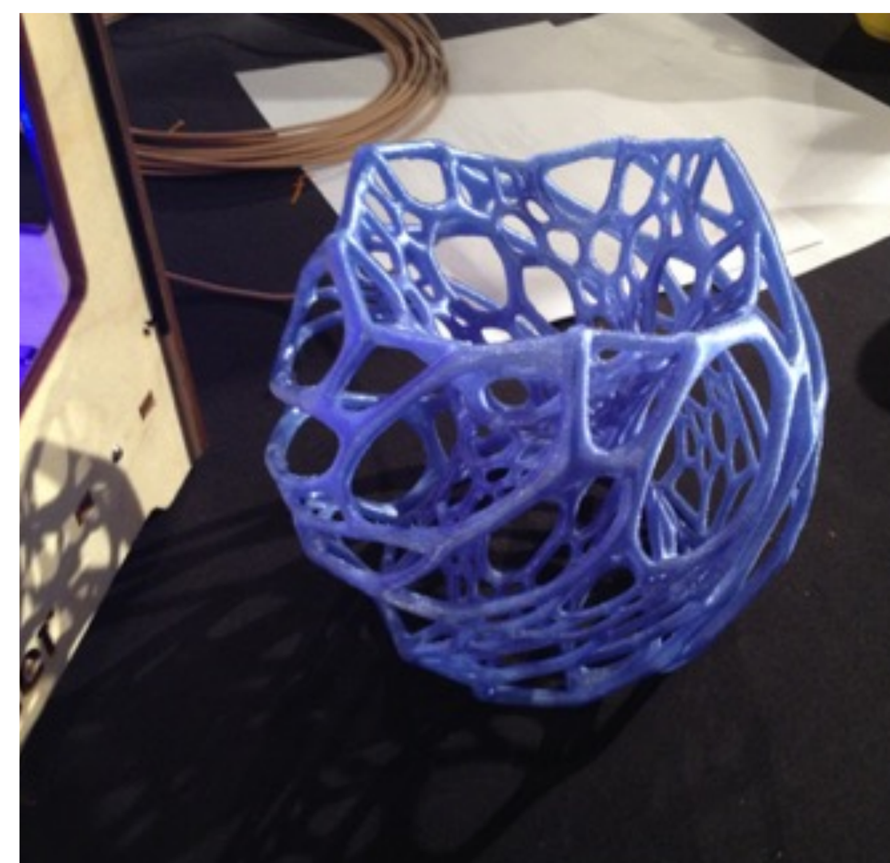




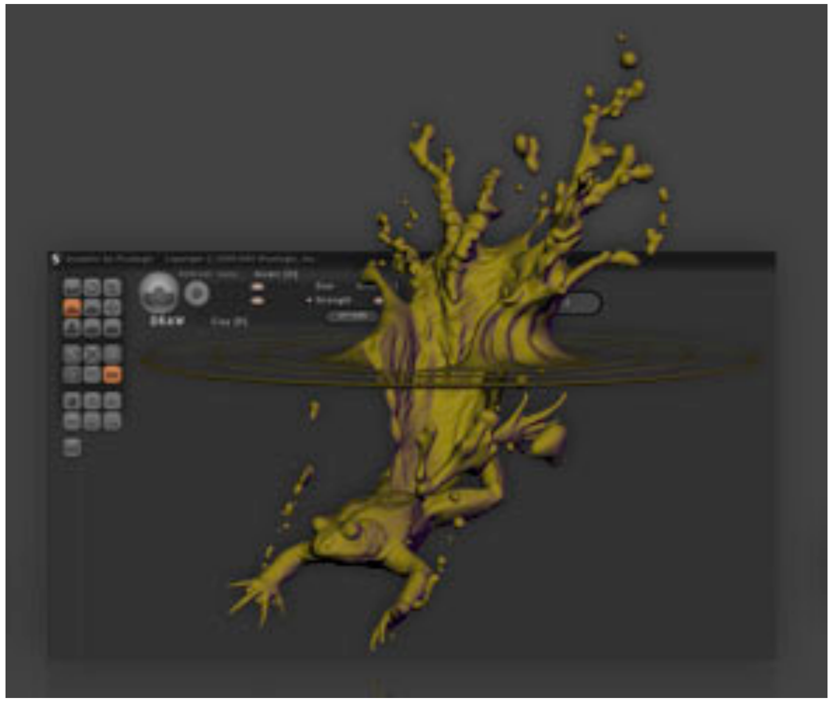
Examples: *free* software for *artistic* 3D modeling

- Sculptris (Win, Mac)
- Autodesk 123D Design (Mac, Win, iPad, web)
- and a few beautiful webapps (e.g. Nervous System)





Sculptris: http://pixologic.com/sculptris/



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:

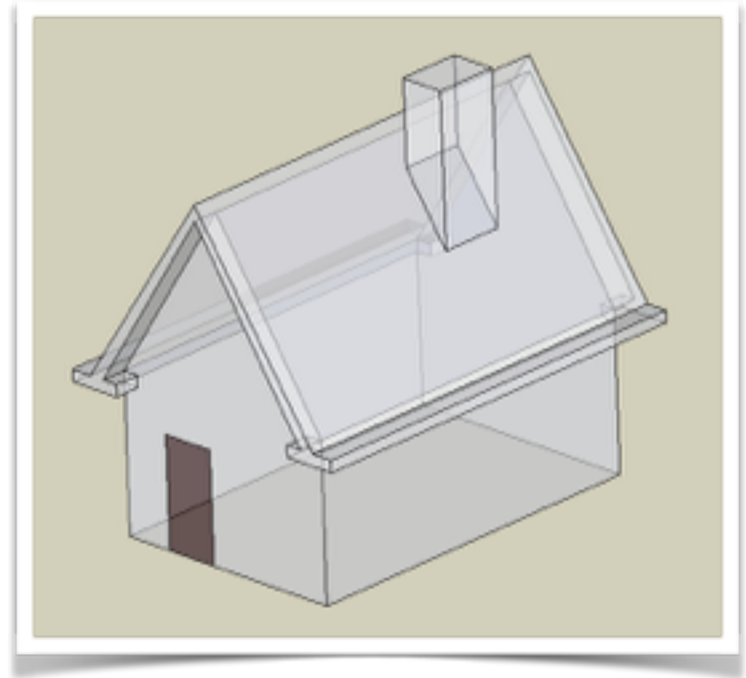
facet normal n_i n_j n_k
outer loop
vertex $v1_x$ $v1_y$ $v1_z$
vertex $v2_x$ $v2_y$ $v2_z$
vertex $v3_x$ $v3_y$ $v3_z$
endloop
endfacet

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.

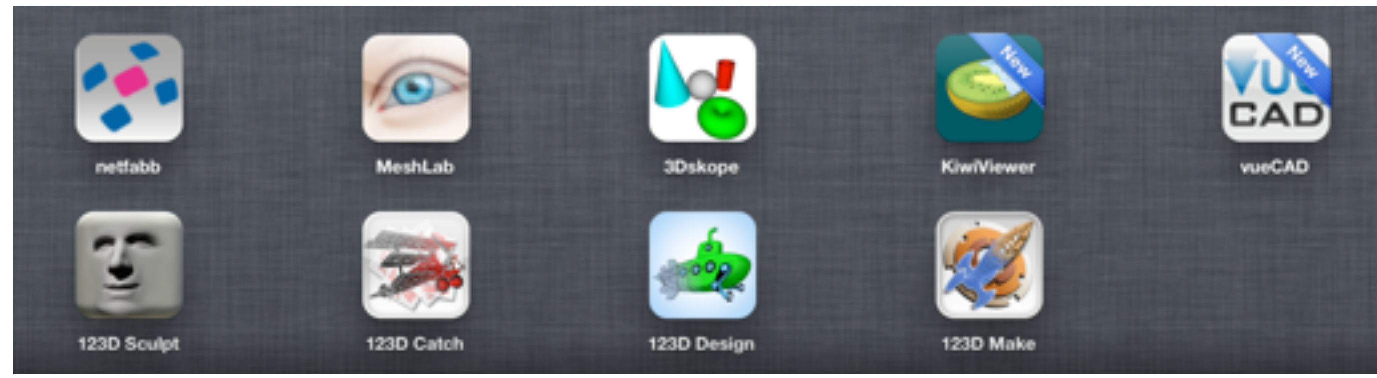
[source: Wikipedia]



```
solid House
facet normal 6.82119751824952e-17 -0.816496580927727 -0.57735026918962 4
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 -0.57735026918962 4
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 -0.57735026918962 4
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 -0.57735026918962 4
```

Free iPad Apps for 3D modeling *with a "touch"*

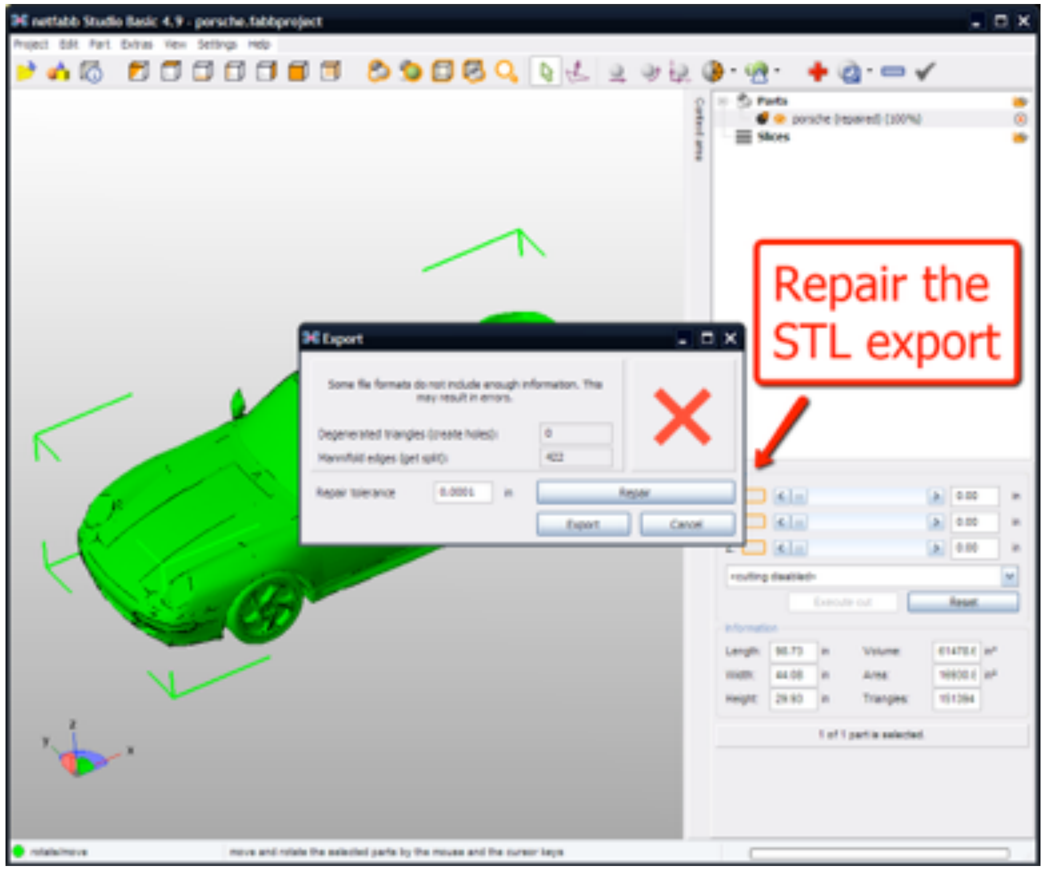
- netfabb (STL viewer only)

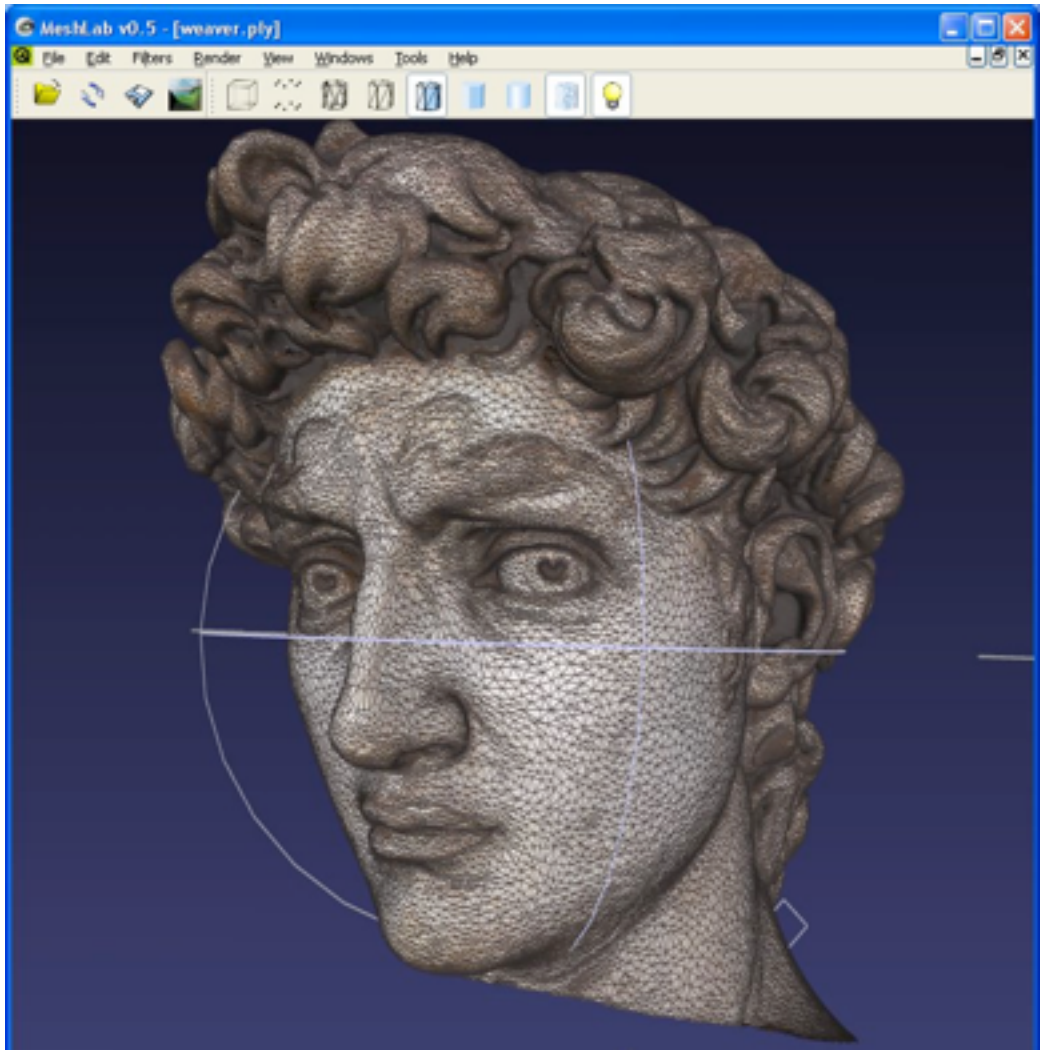


- MeshLab (STL viewer only)
- other viewers (3Dskope, KiwiViewer, vueCAD)
- Autodesk: 123D Sculpt ("*rounded*"), 123D Design ("*squared*")
- Autodesk 123D Catch (3D scanning with iPad/iPhone camera)
- Autodesk 123D Make (cardboard 3D models! ;-)

#2 - Check & repair

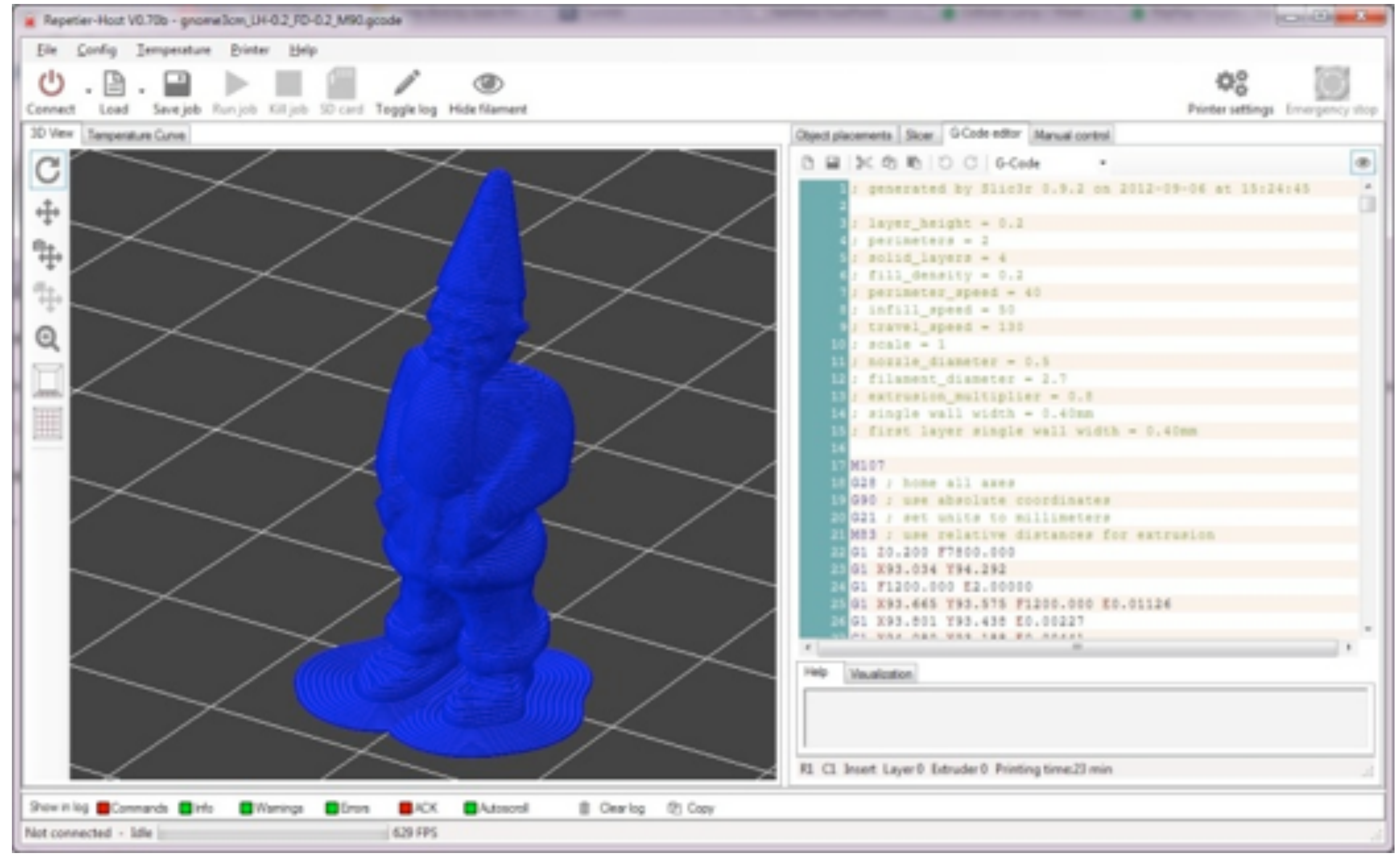
- The STL files that have been created by the modeling software may not be yet ready for printing, they should be checked for problems.
- Software for control and repair:
  - **netfabb** Studio Basic
  - **MeshLab** (conversion too)
- Software for visualization:
  - **Pleasant3D** (Mac only)

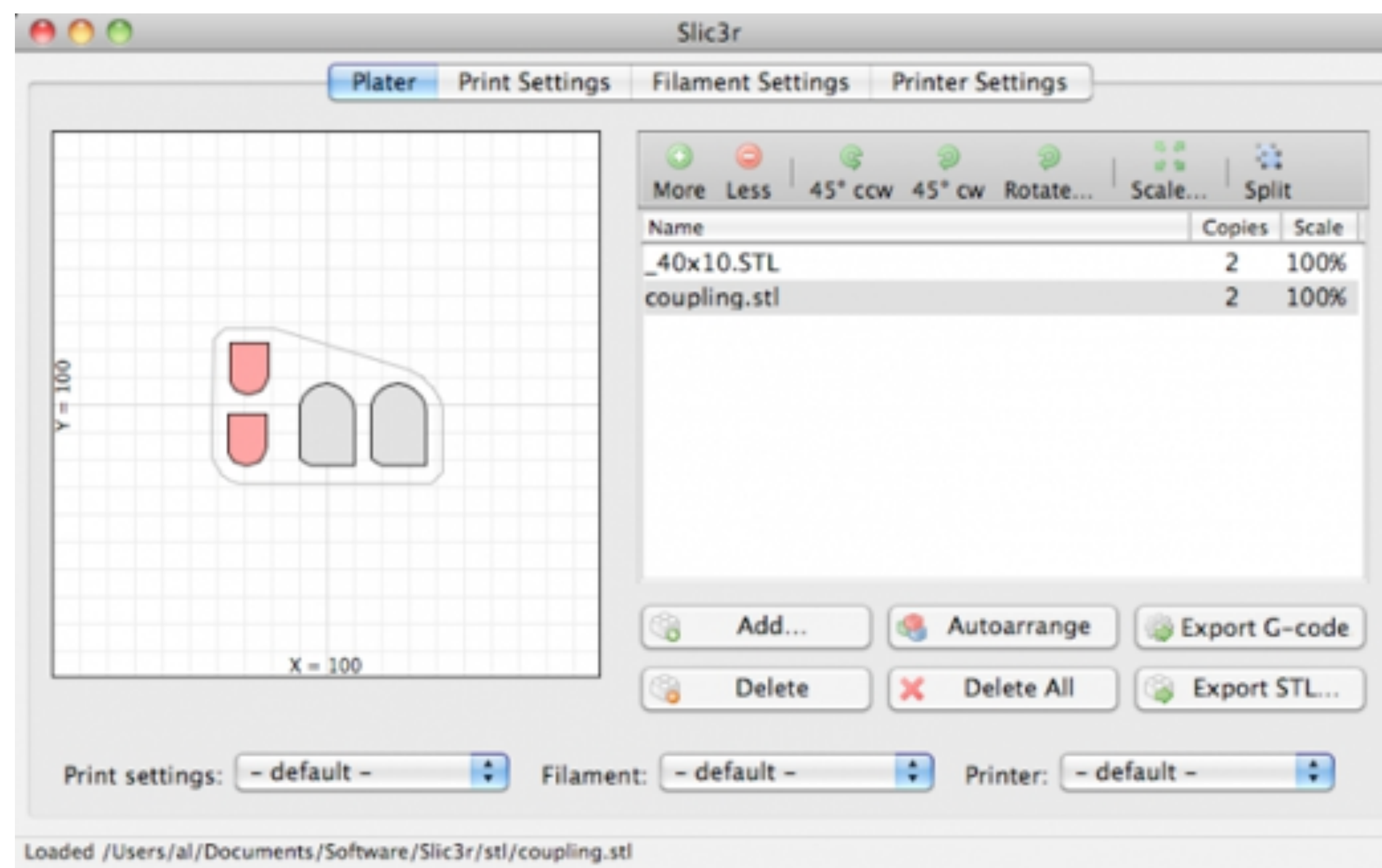




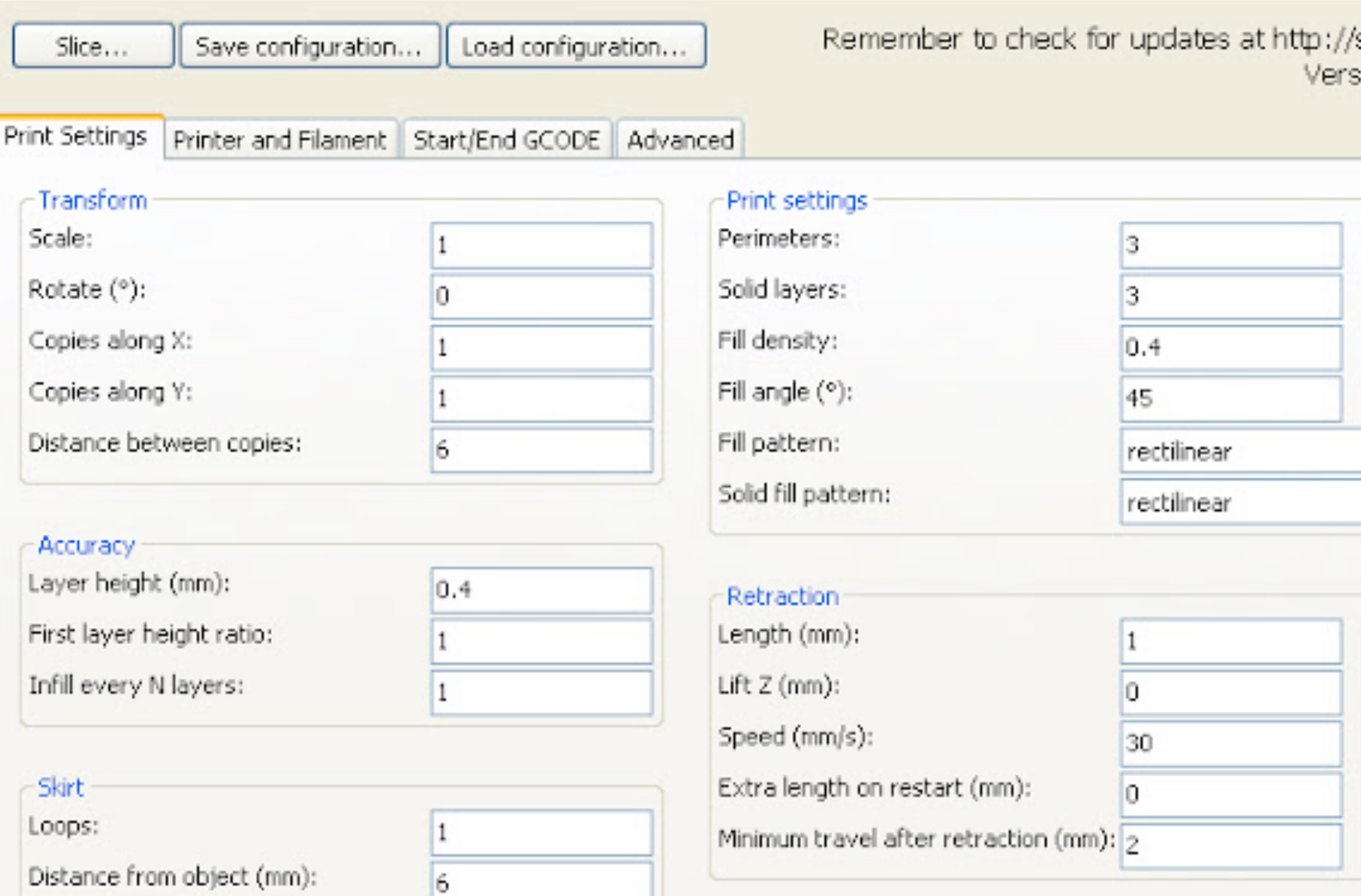
#3 - Slice

- *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*.



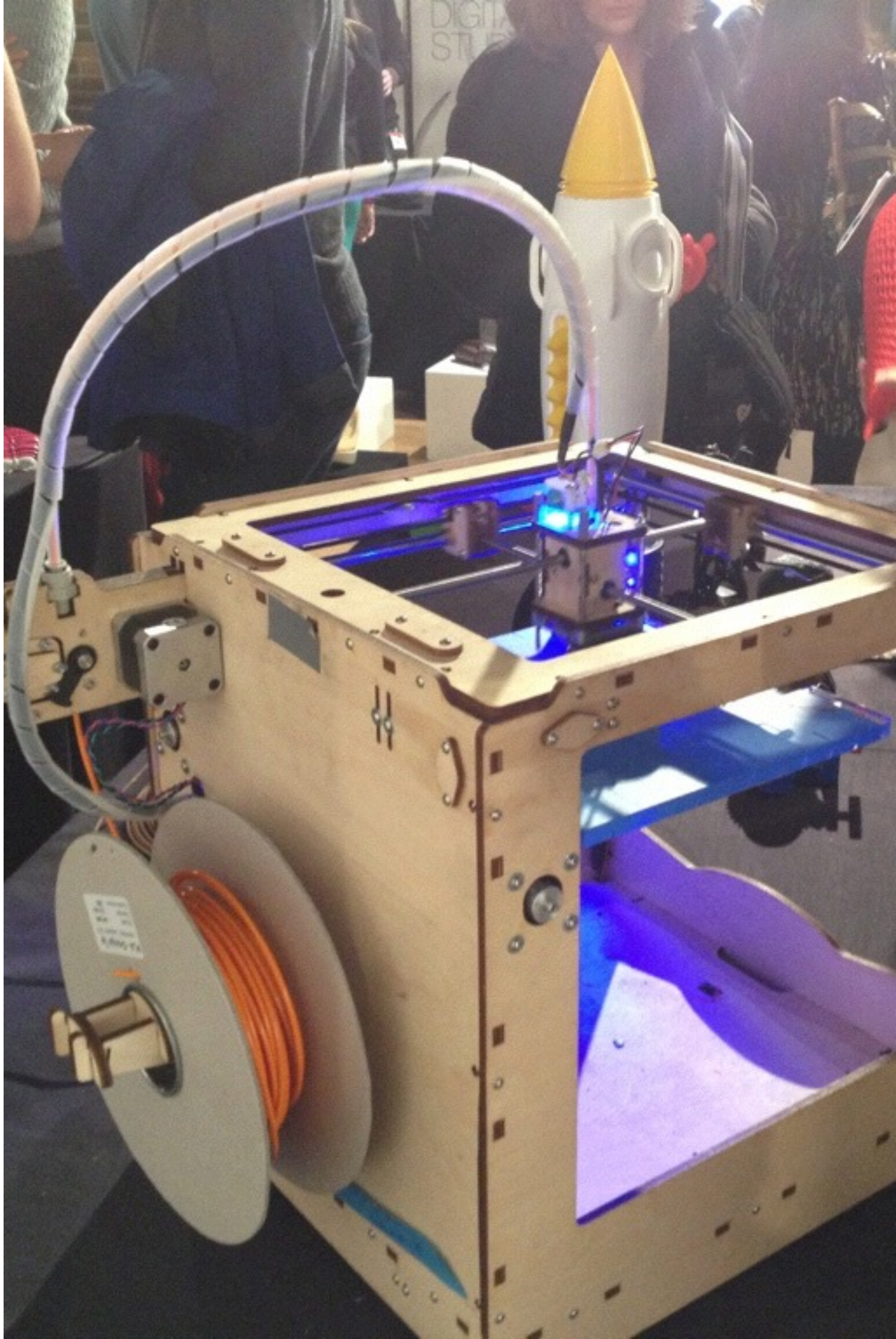


An example: Slic3r



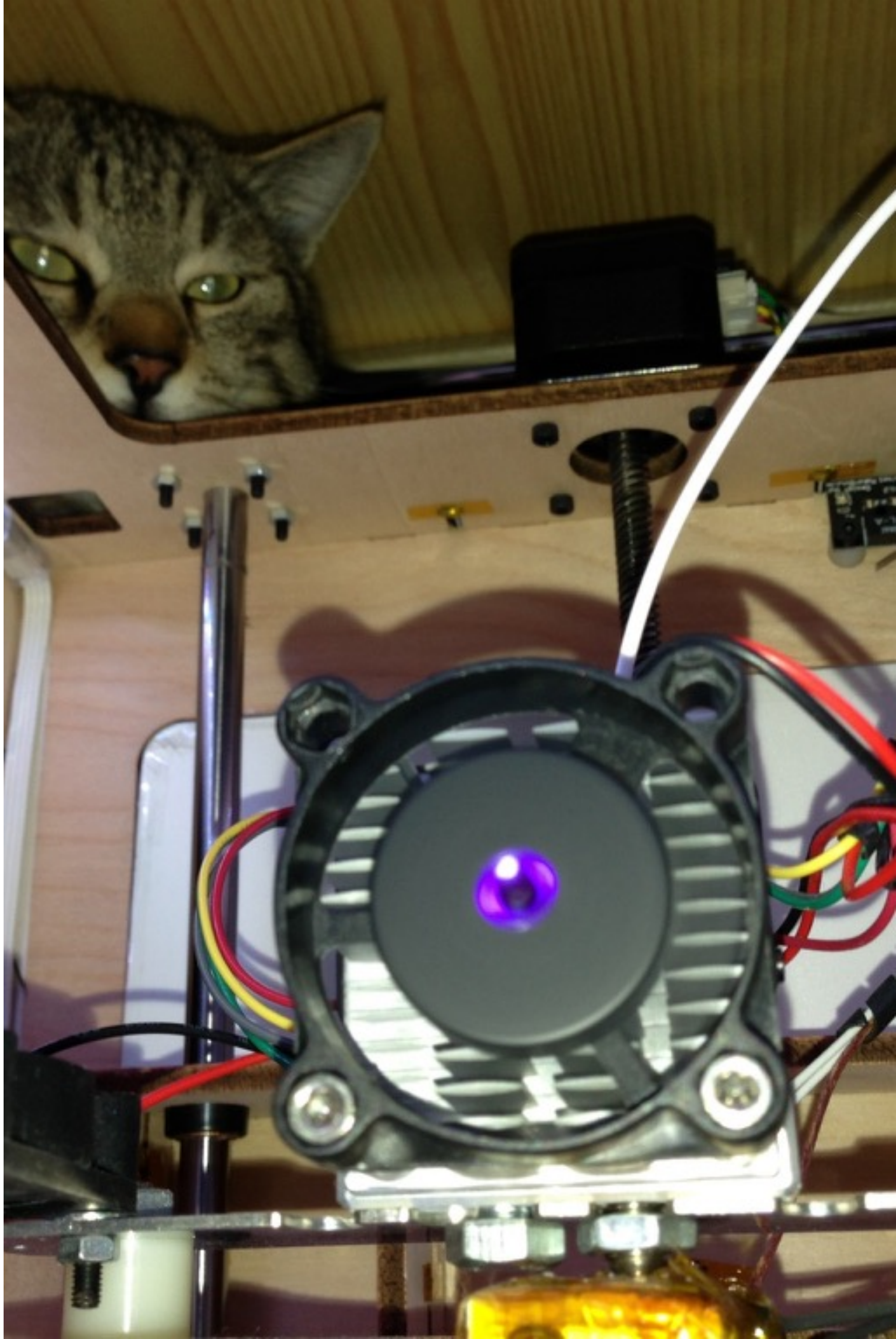
#4 - Prepare the printer

- 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 ;-)



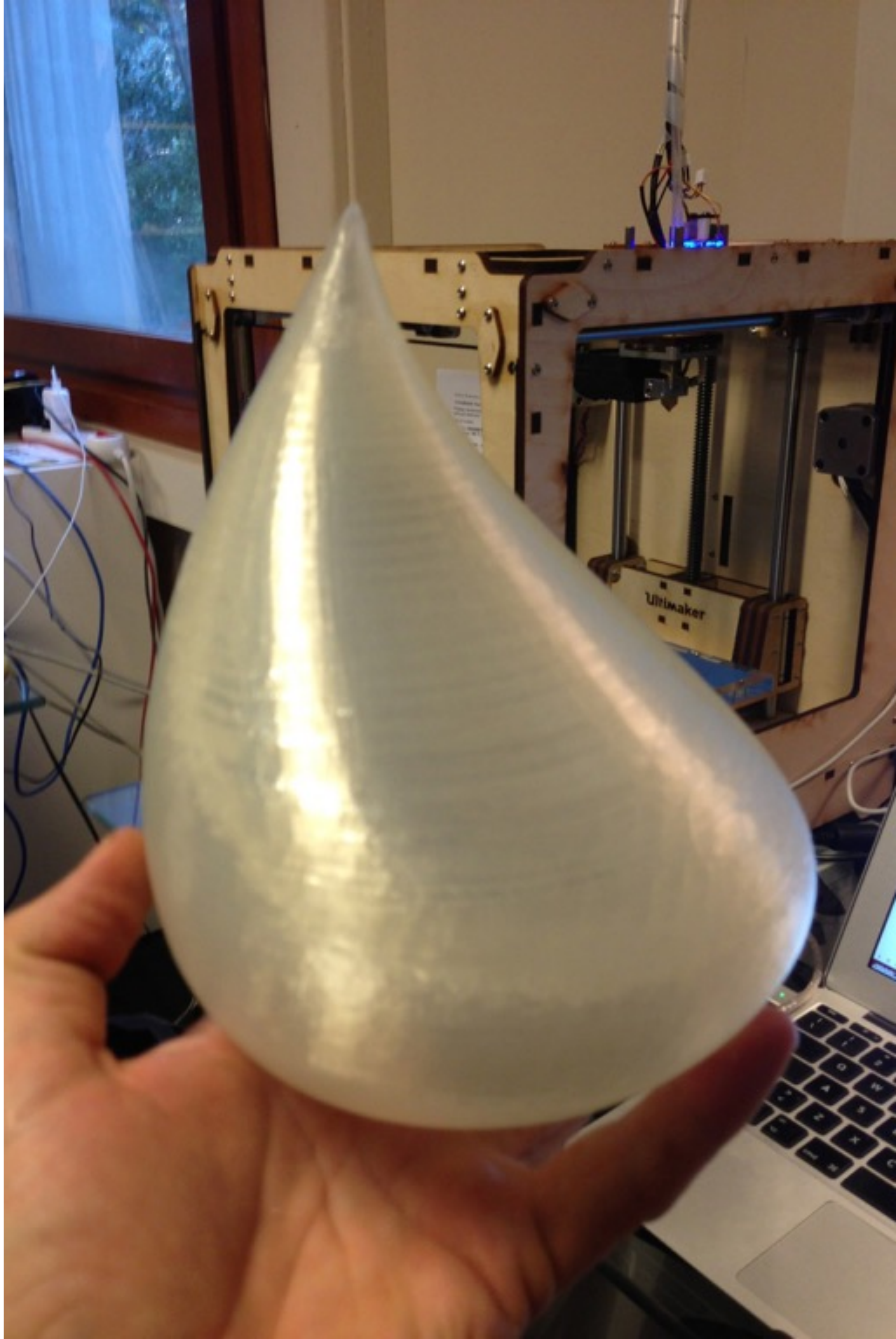
#5 - Wait until finished

- 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 > 200ºC, melted plastic, electricity, moving parts, wooden frame...).



#6 - Finishing

- 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.



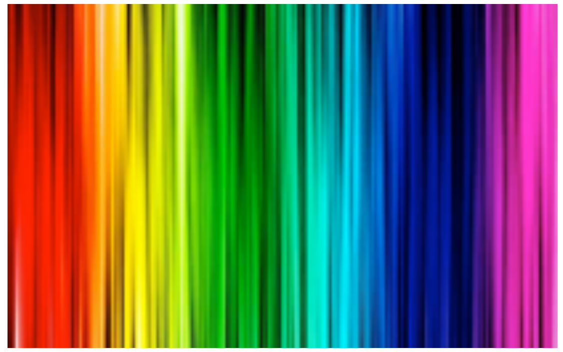
A world of plastic

don't pollute,
3D-print!

Many types of plastics

- **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



- 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

www.perpetualplasticproject.com

- make 3D-printed objects from recycled plastic

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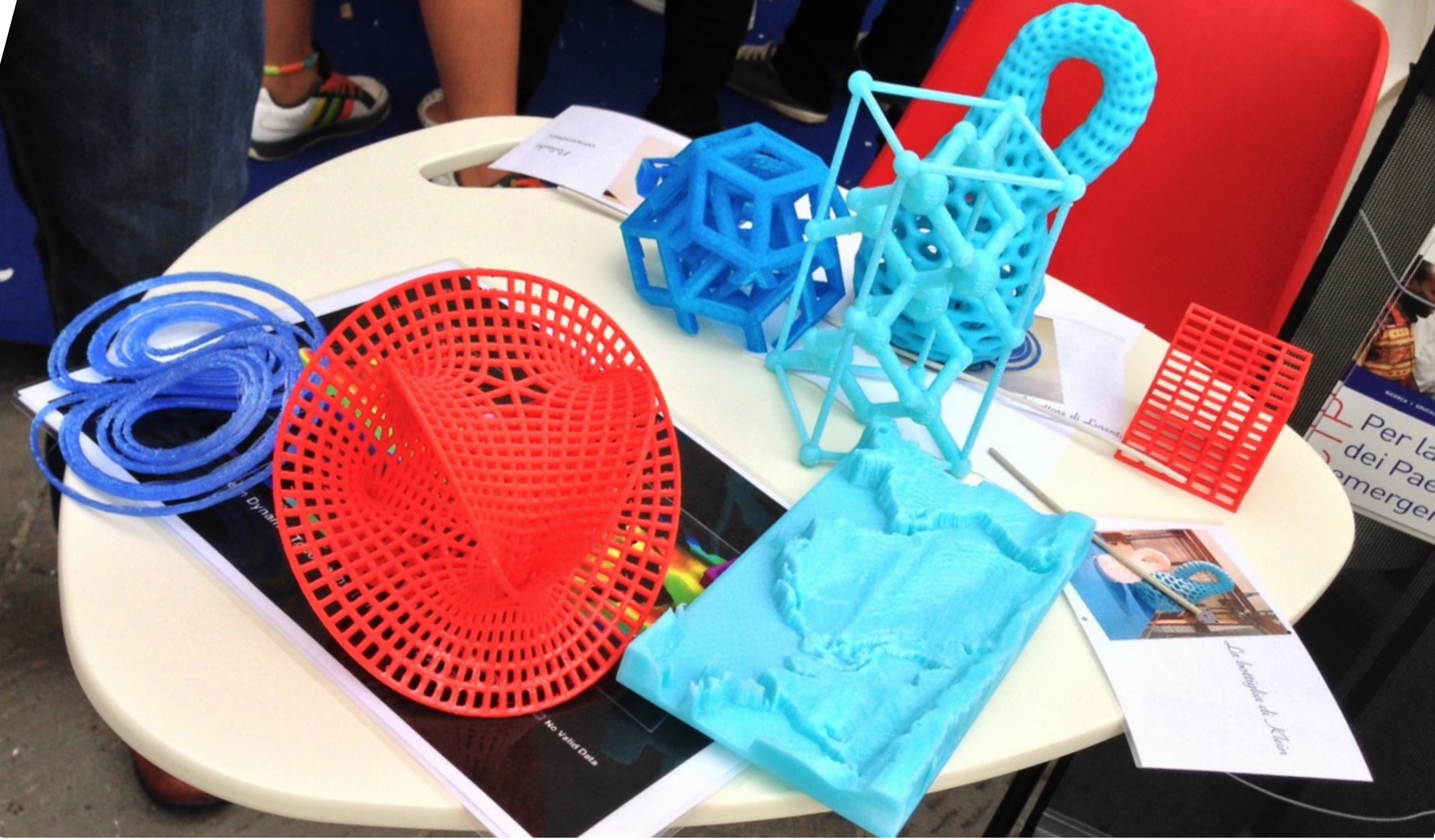
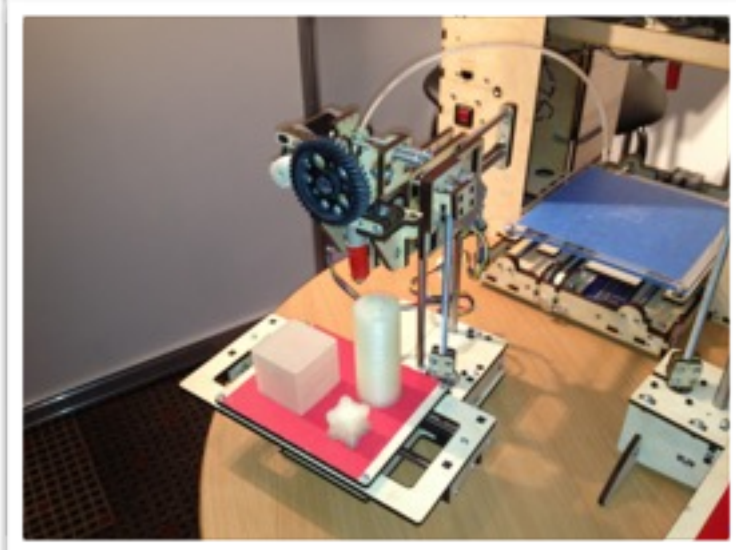


Scientific applications of low-cost 3D printing

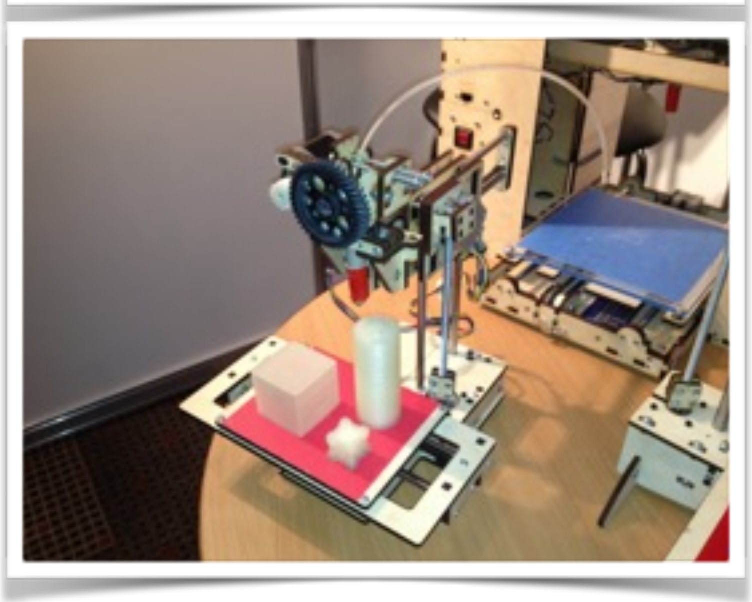
... And other interesting things!

Small is beautiful



Small is beautiful

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



Small is beautiful

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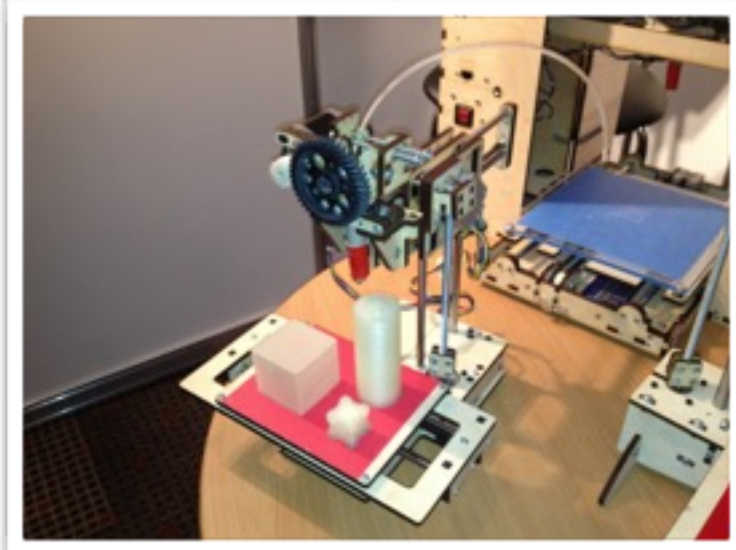
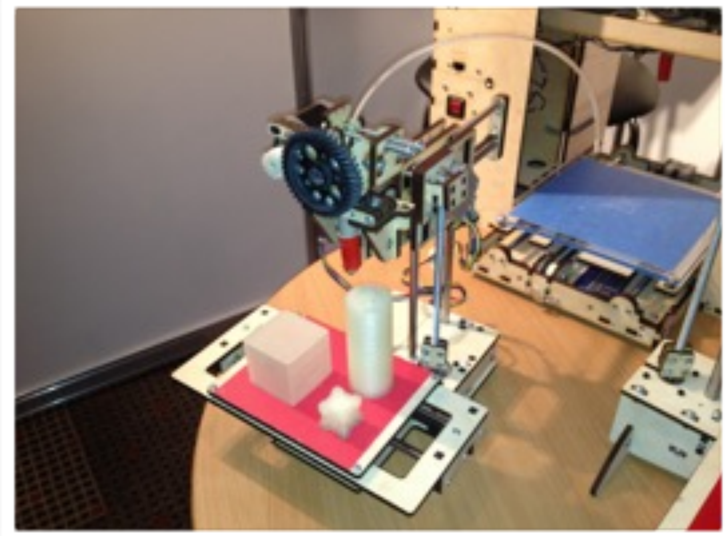
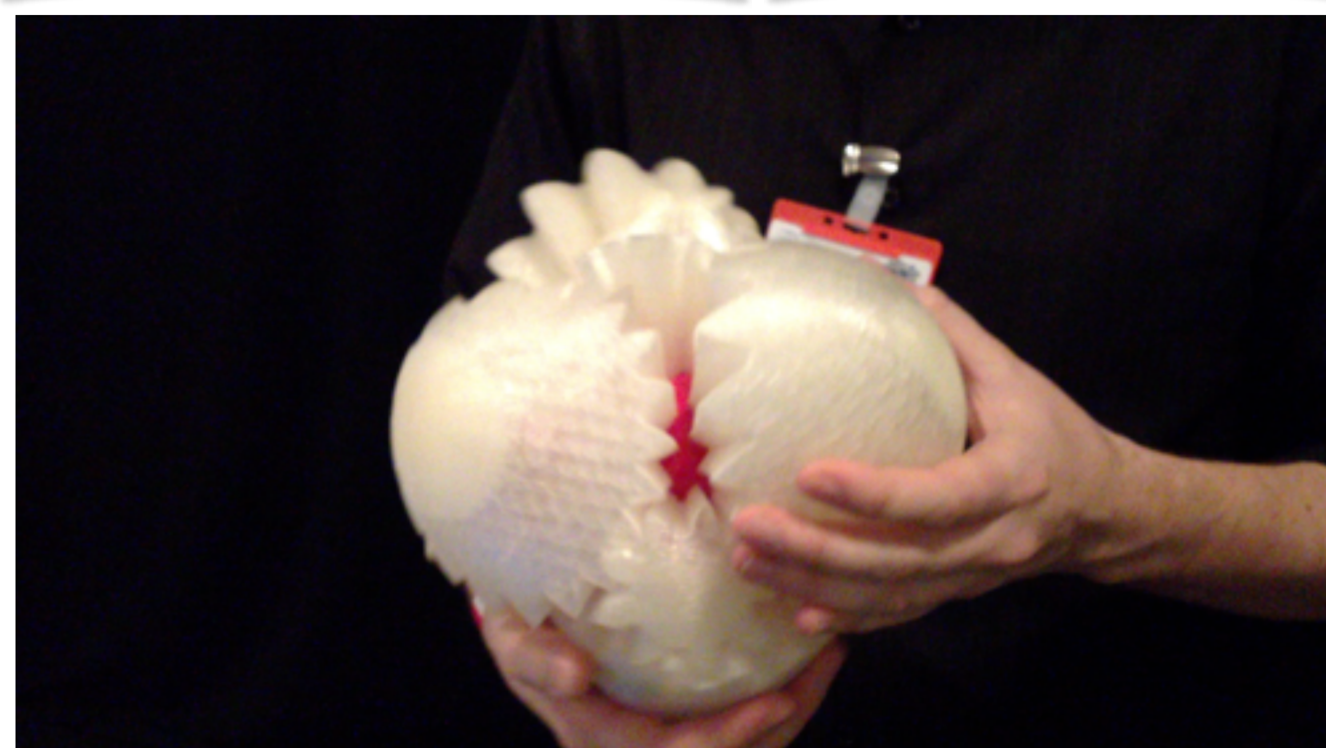
- In some models isn't very difficult to increase the vertical size. Horizontal limits are harder to break.



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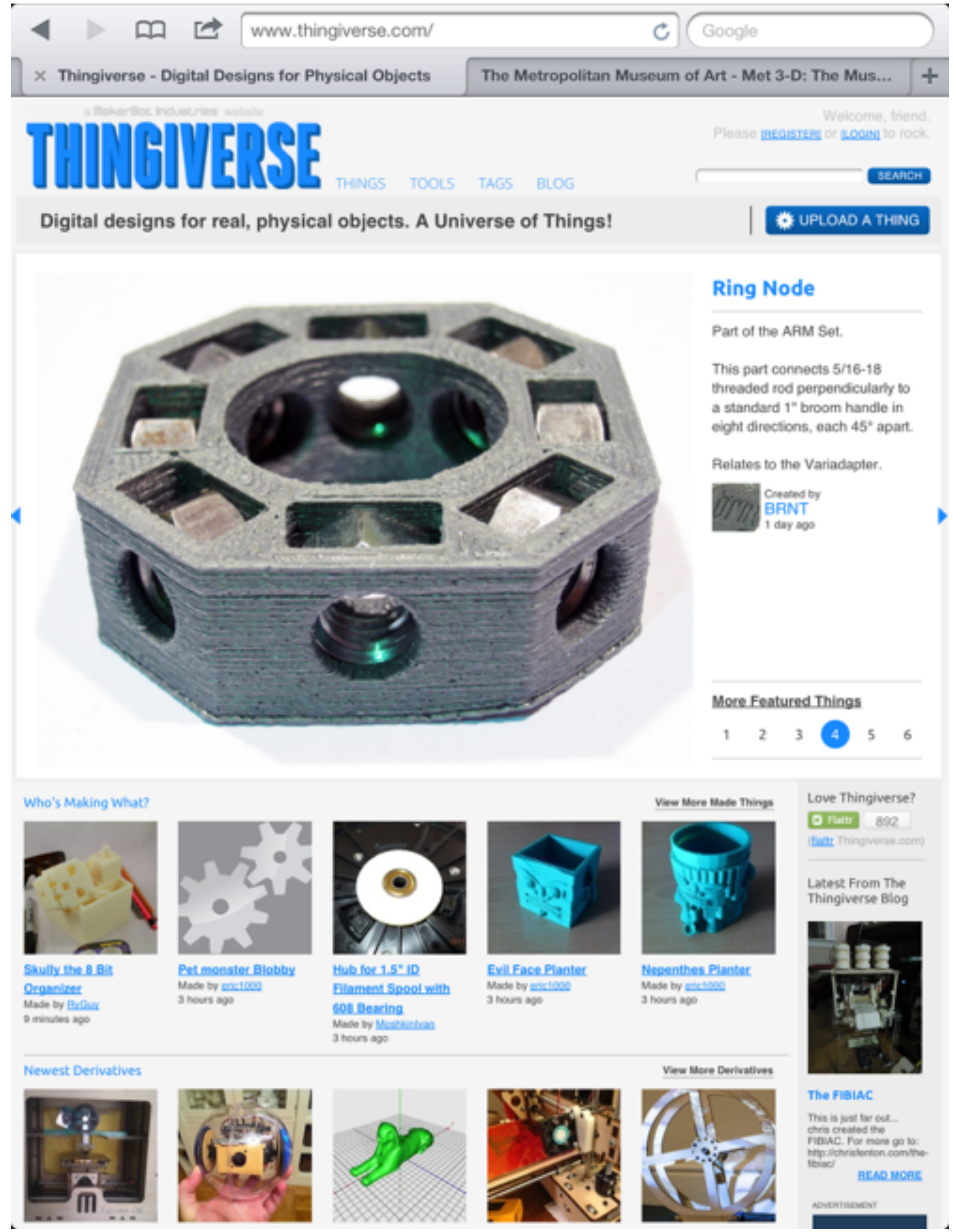
During the summer of 2012, the Metropolitan Museum of Art held an event to make 3D scans and prints of works from throughout the museum. Participants used digital cameras and Autodesk's 123D Catch to generate the 3D models, and then printed them using MakerBot Replicators.

Met3D

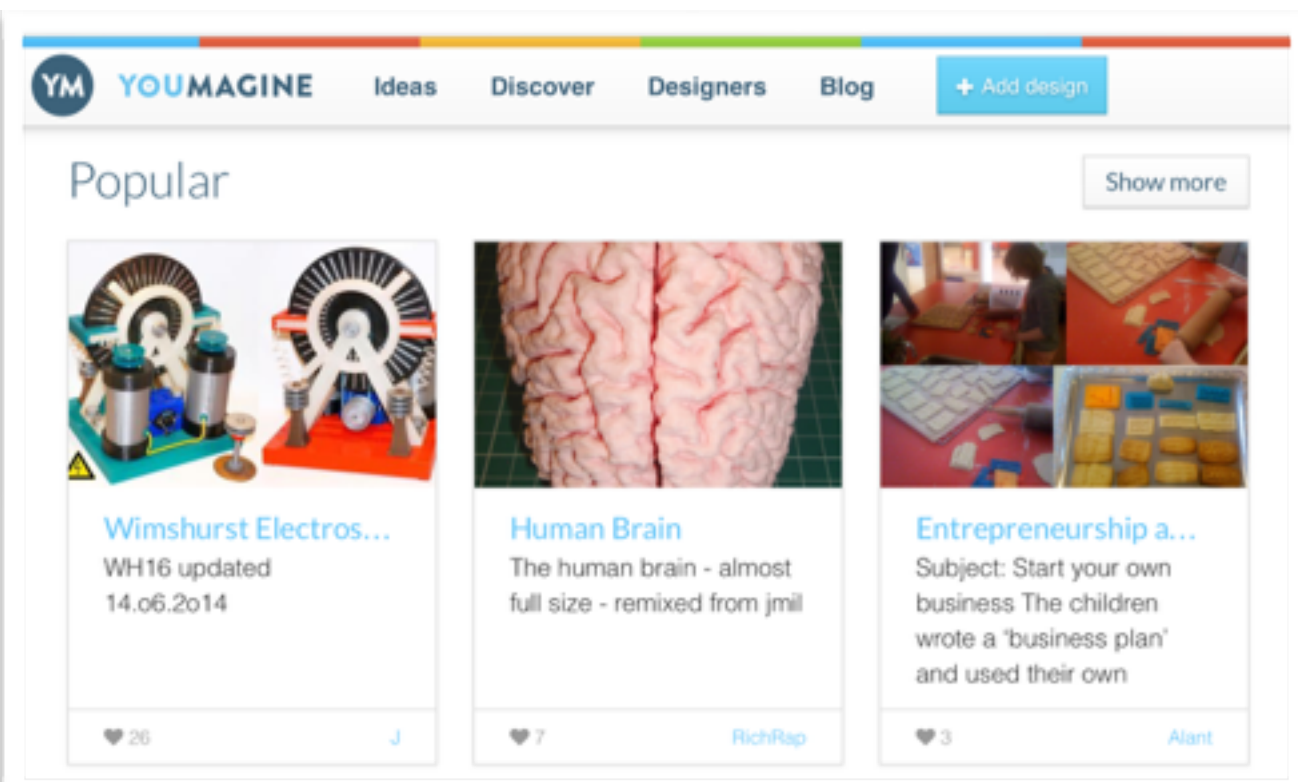
Making ***new*** objects

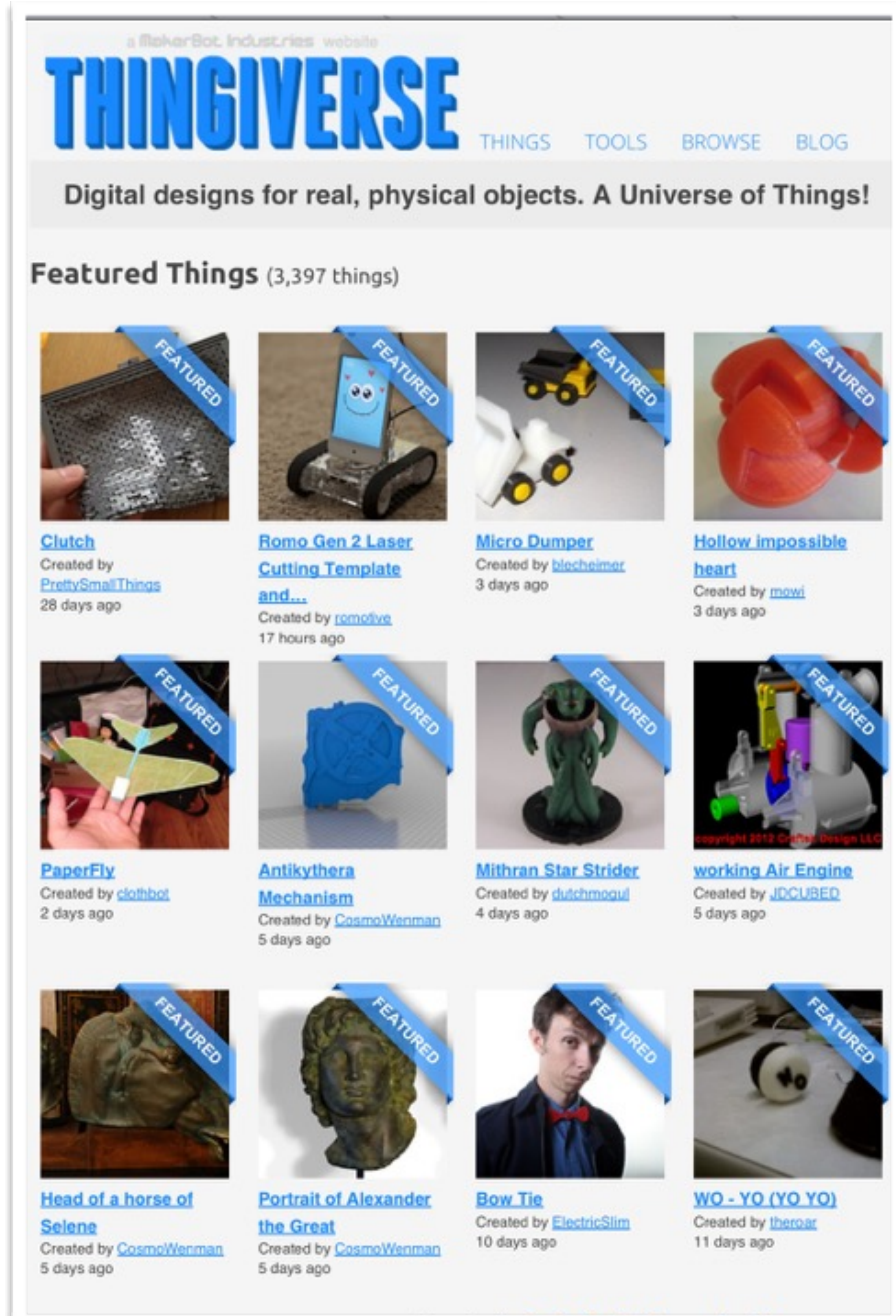
- 3D printing isn't just about *copying* objects, but also about *creating new things*, that are impossible (or expensive, or difficult) to make with other technologies. **At home!**



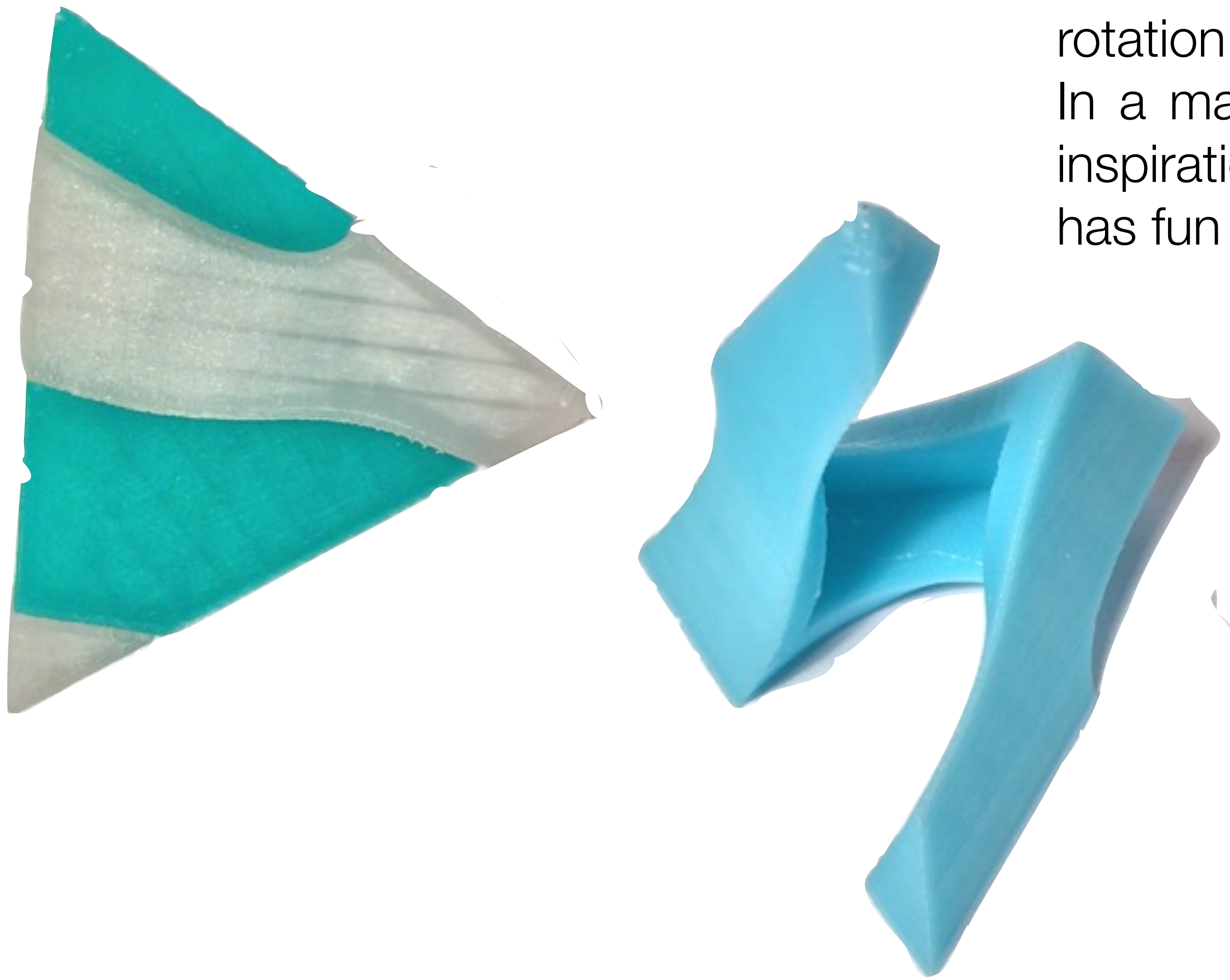
Thingiverse & C.

- www.thingiverse.com
- 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.

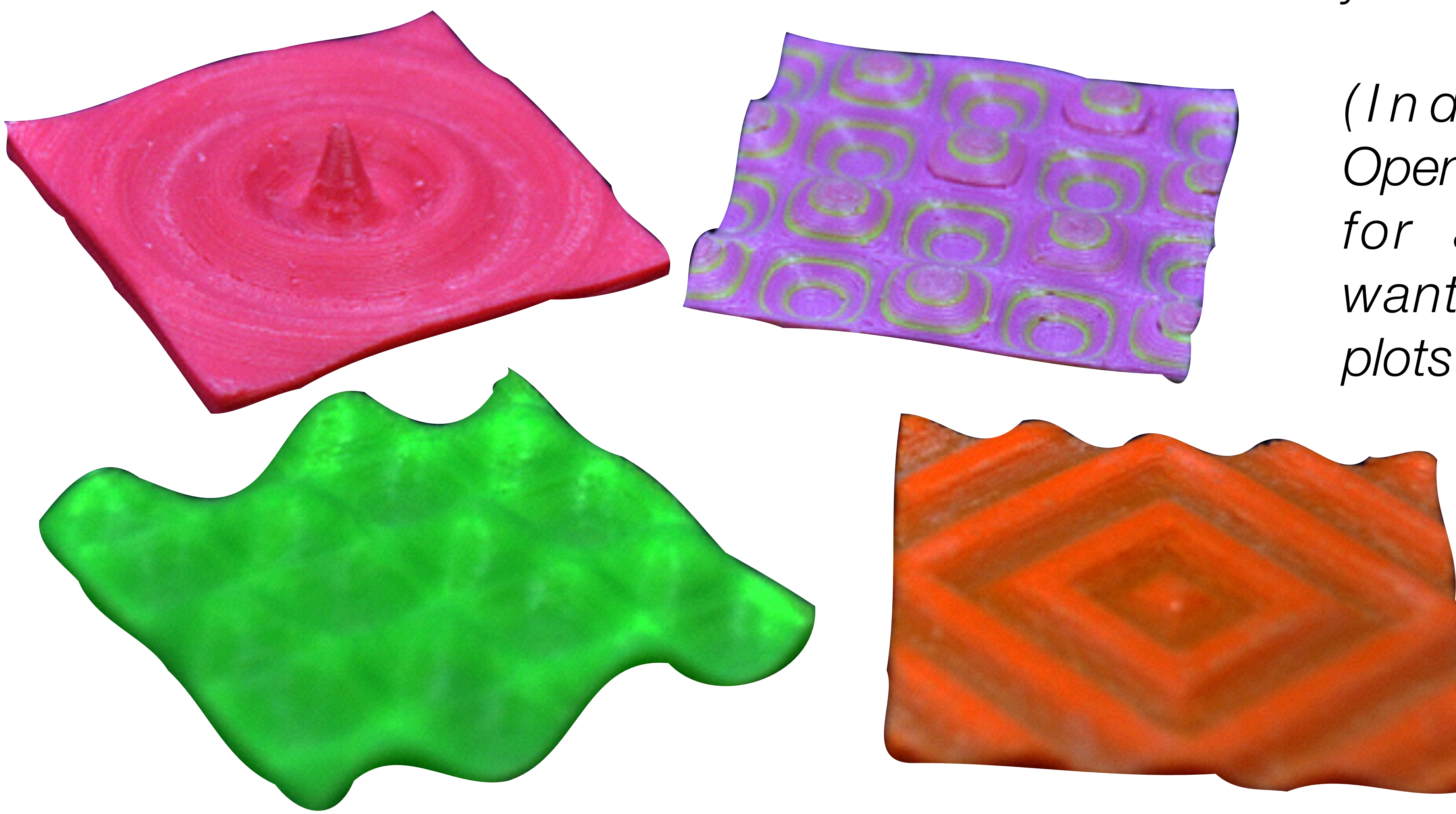


Screw-puzzle by George Hart

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

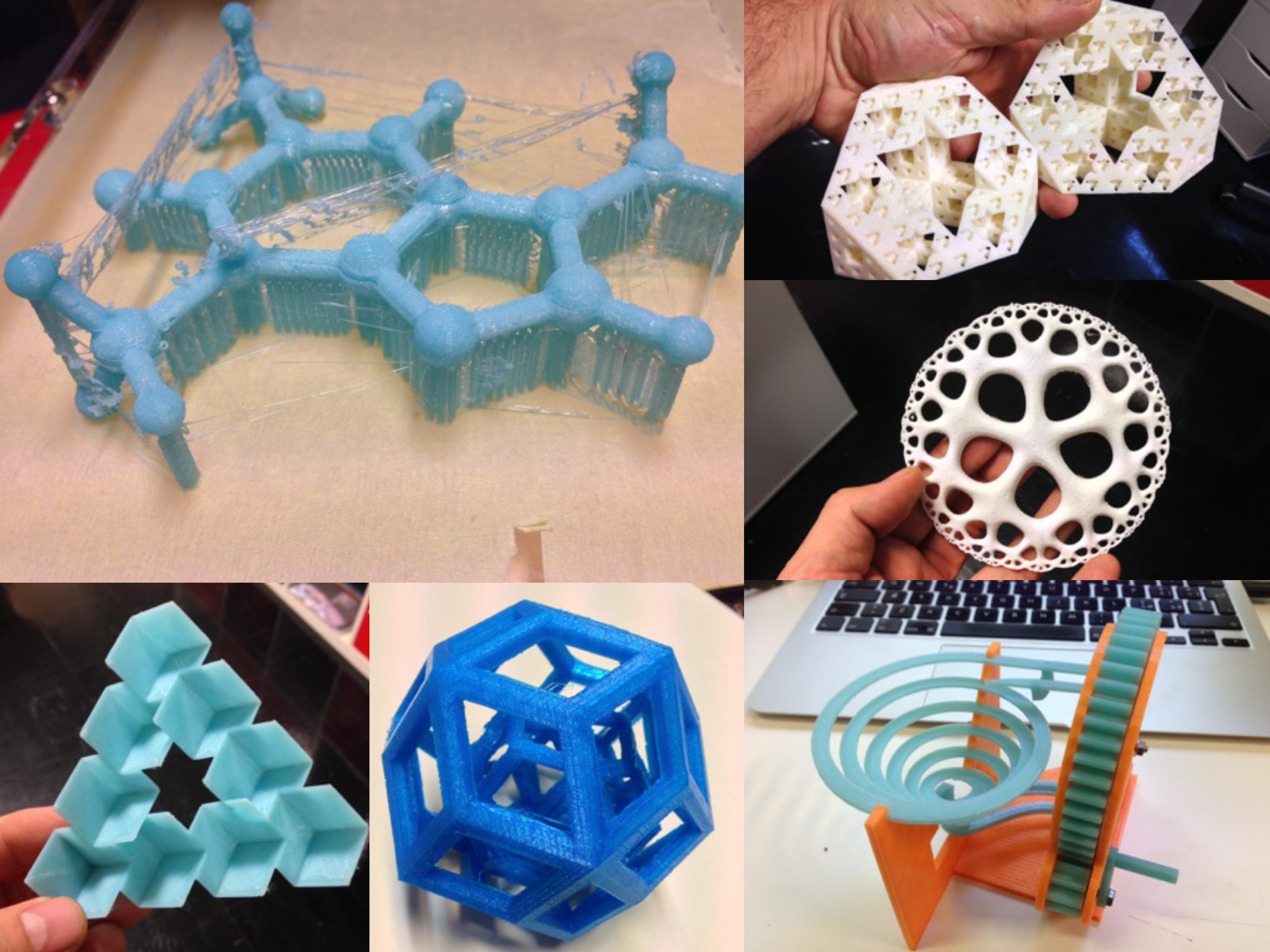
"Could there be anything more fun than drawing 3D surface plots?
Yes, you can 3D print 3D surface plots and hold them in your own hands!

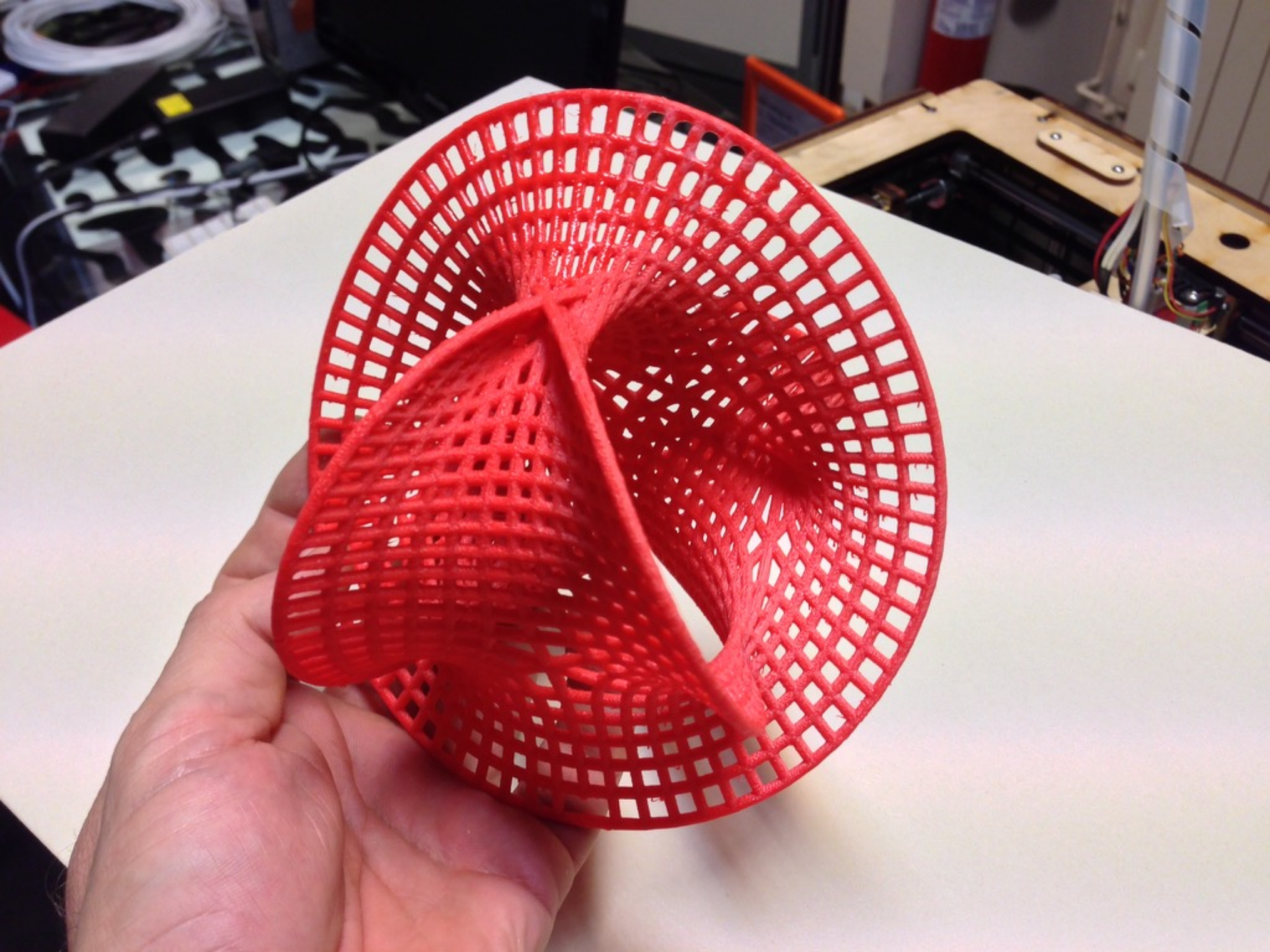
(Indeed, I wrote this OpenSCAD program in 2011 for a math teacher who wanted some tangible 3D plots for a blind student.)"

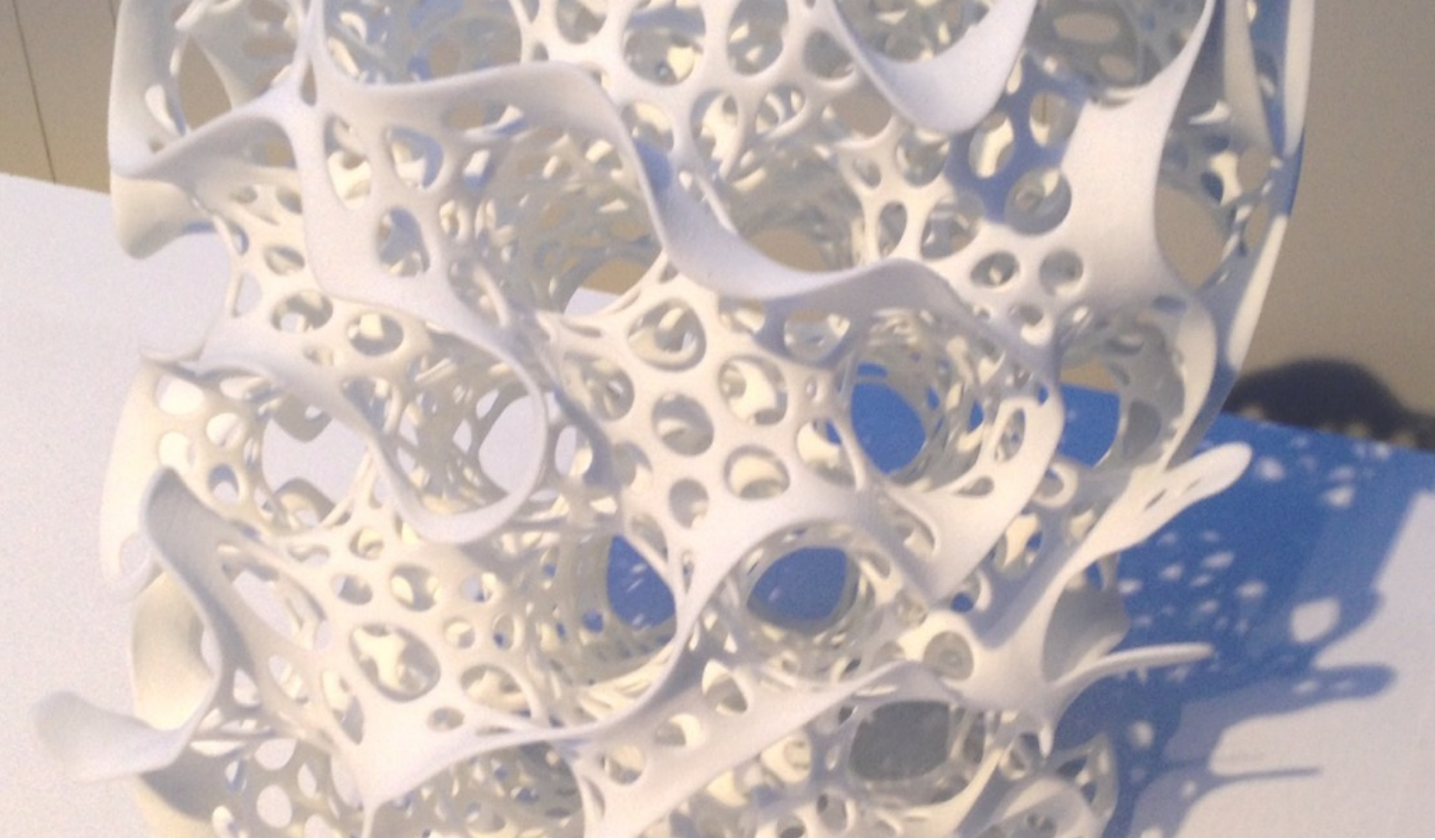


OpenSCAD 3D Surface Plotter

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...

The Abdus Salam
International Centre
for Theoretical Physics
www.ictp.it

United Nations Educational, Scientific and Cultural Organization

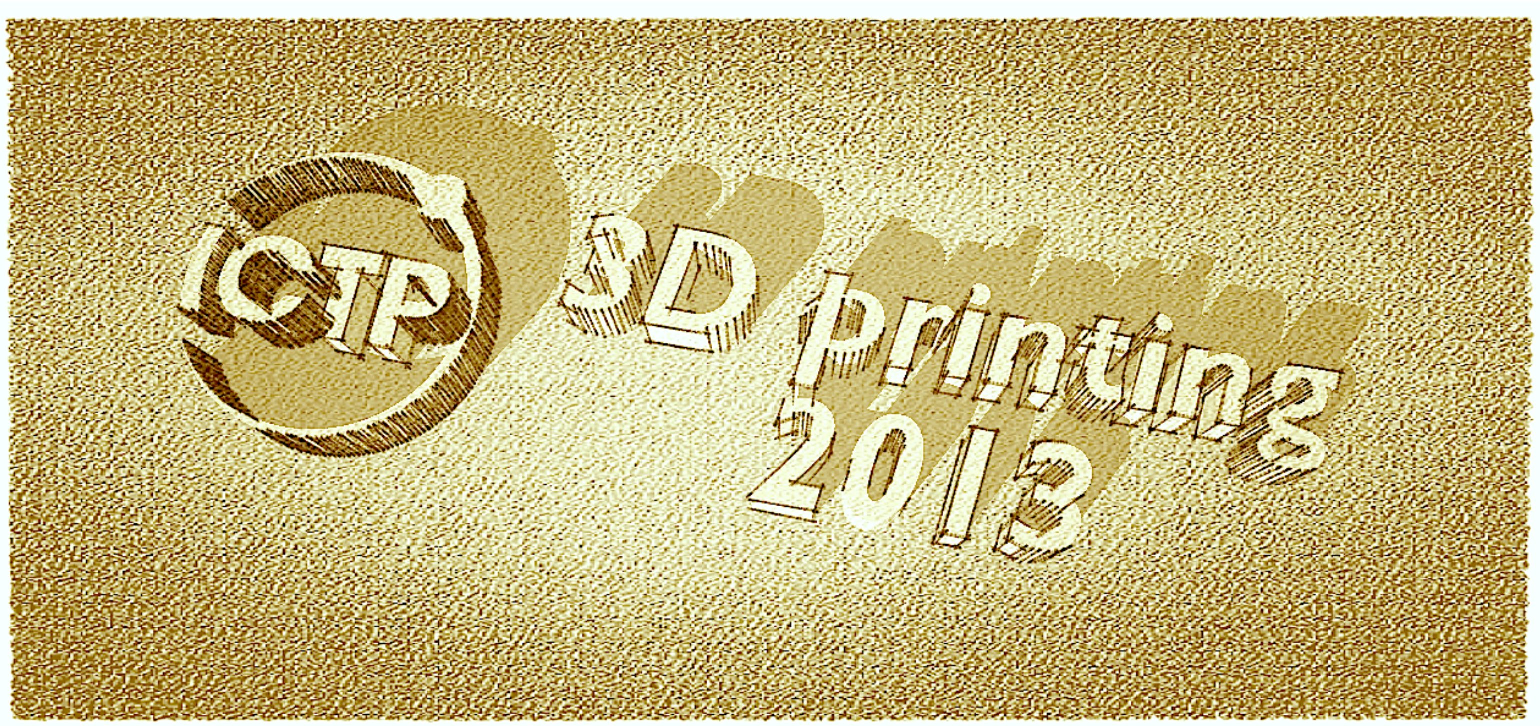
IAEA International Atomic Energy Agency

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
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M. ZENNARO

An article on Nature

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

nature International weekly journal of science

Commendations for *Nature* News & Comment in the 2012 Online Media Awards

NATURE | NEWS FEATURE

Science in three dimensions: The print revolution

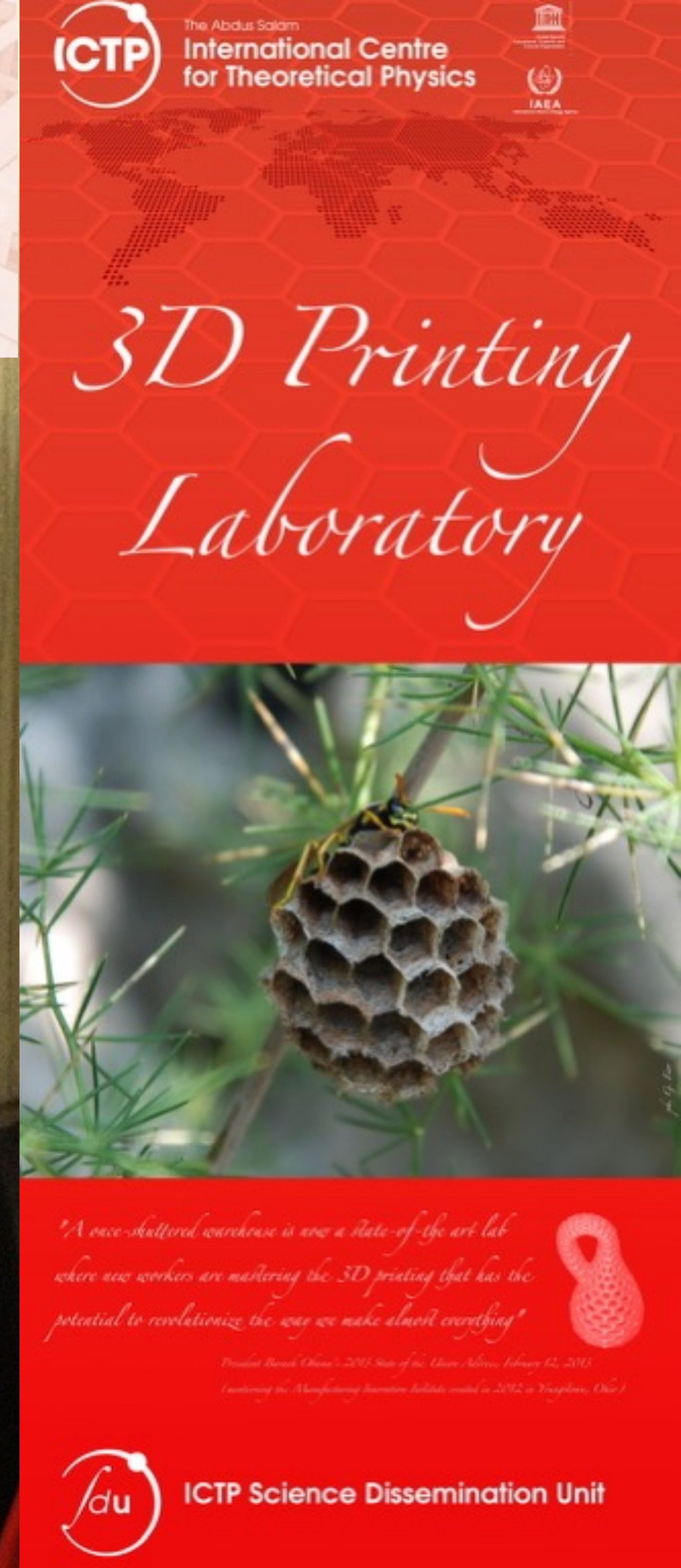
Three-dimensional printers are opening up new worlds to research.

Nicola Jones

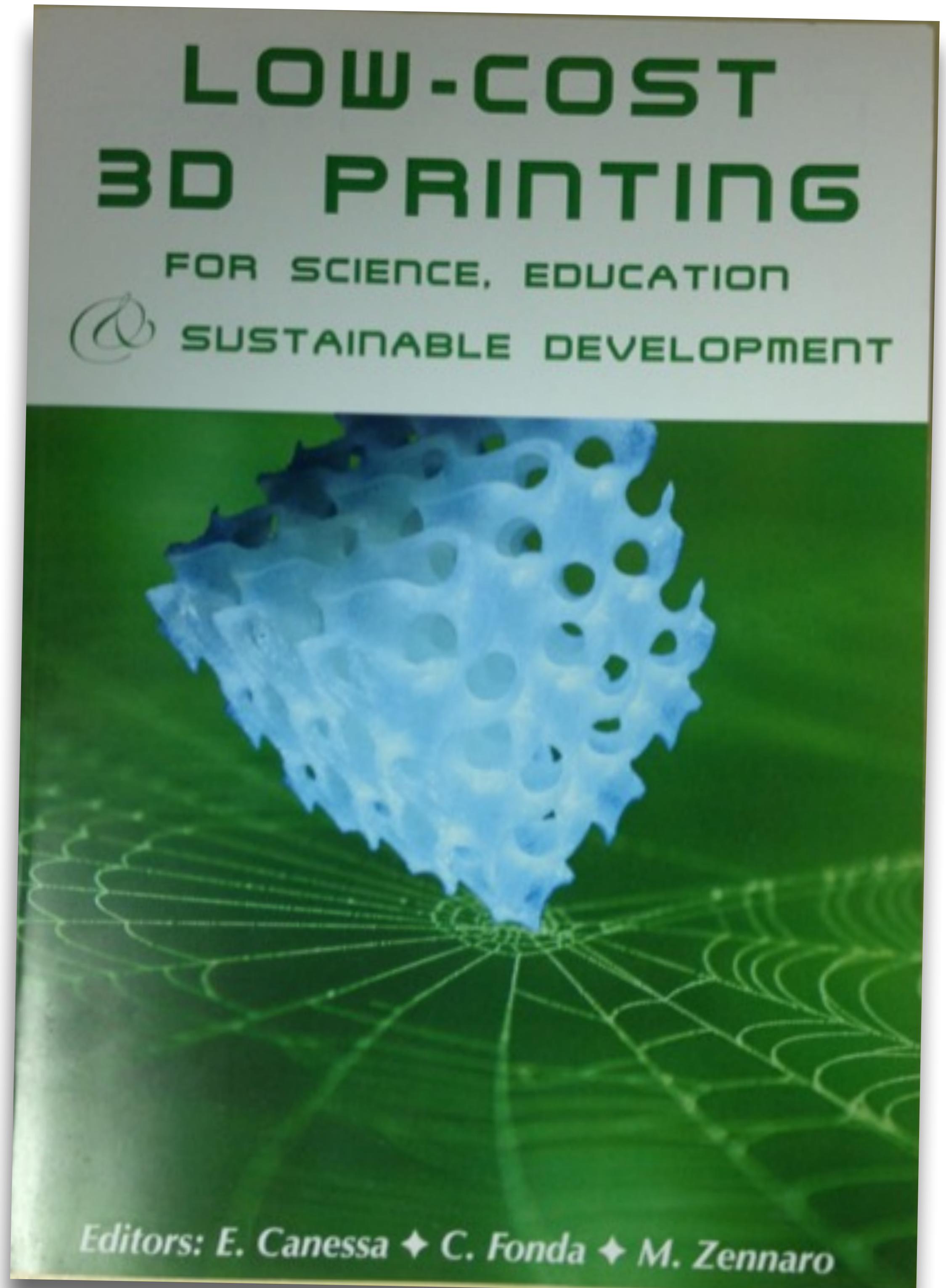
04 July 2012

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.


The Abdus Salam
International Centre
for Theoretical Physics
3D Printing Laboratory


The Abdus Salam
International Centre
for Theoretical Physics
IAEA
3D Printing Laboratory
"A once-shuttered 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
(mentioning the Manufacturing Innovation Institute created in 2012 in Youngstown, Ohio)
ICTP Science Dissemination Unit

A free and open book (and eBook):



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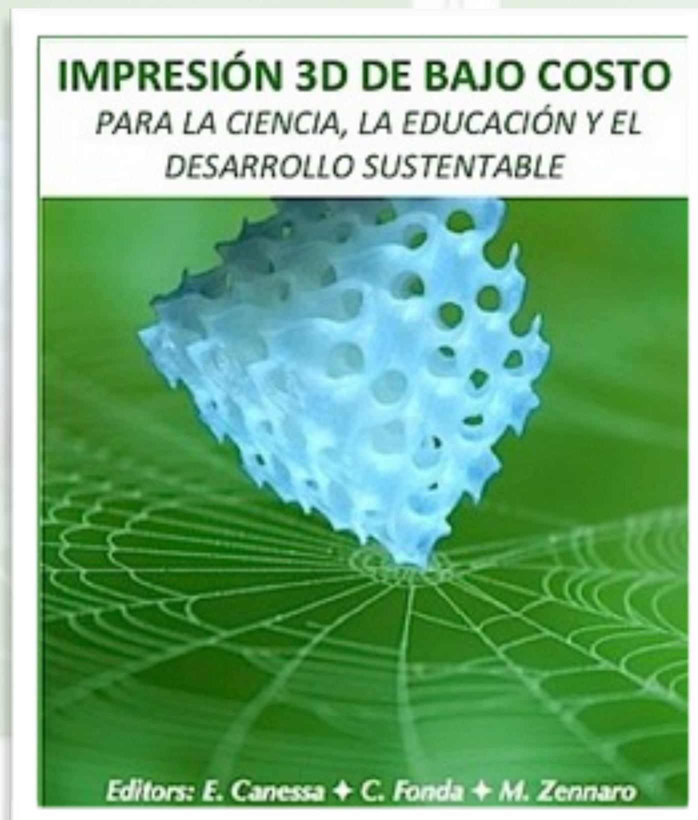

Korean

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

sdu.ictp.it/3D

FabLab

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


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