

# Things you ~~cannot~~ <sup>only</sup> 3D-print

(spunti per un nuovo approccio al design creativo,  
nell'epoca delle stampanti 3D alla portata di tutti)

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(ICTP) Trieste, Italy



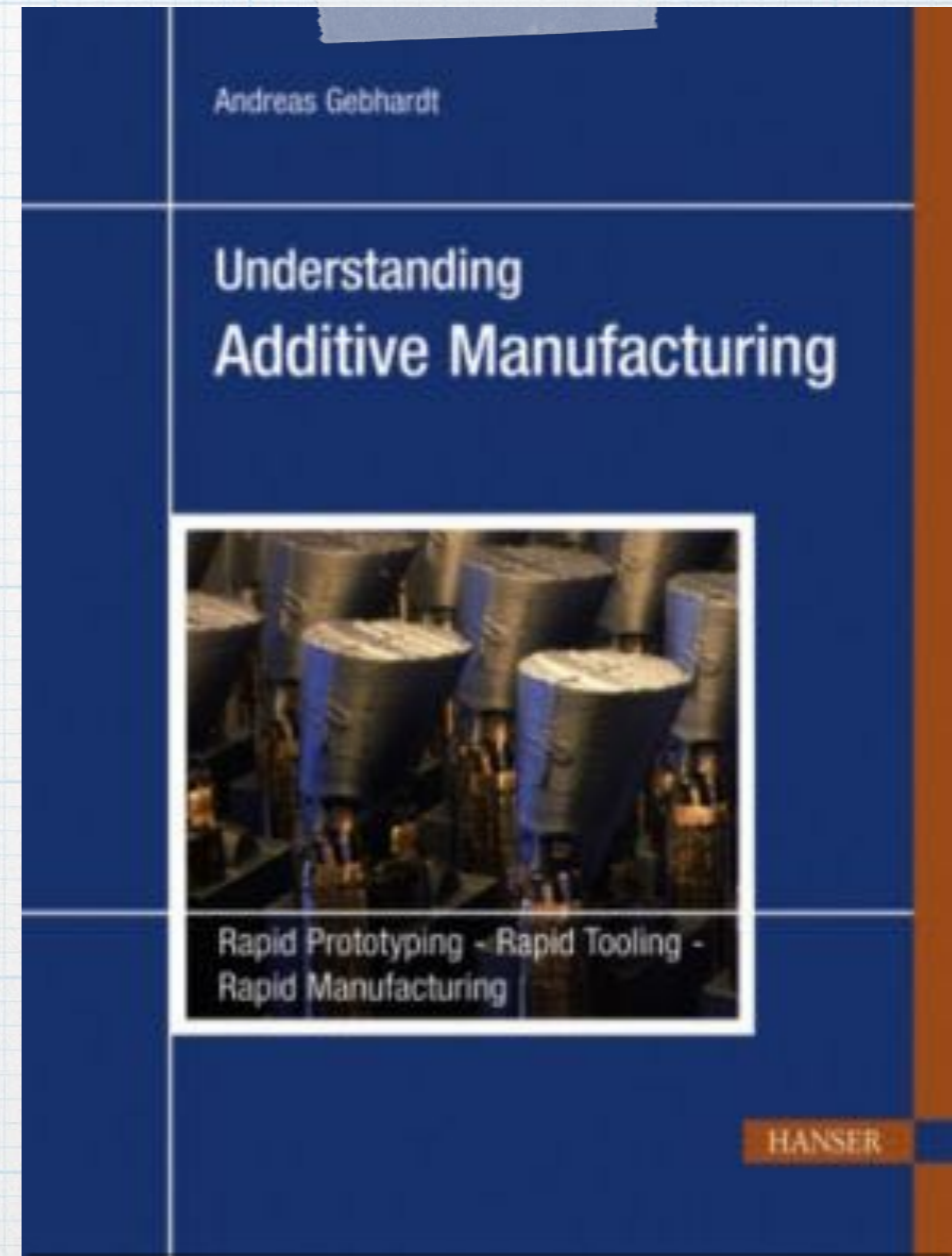
# 3DP in 3 hours

- 3D printing *short* intro (FDM)
- Mesh & mesh issues
- Slicing (science or art?)
- Common problems & solutions
- Beyond the usual models: design objects meant to be 3D printed



# 3DP is addi(c)tive!

- 3D printing is an *additive manufacturing* technology, opposed to the more common *subtractive manufacturing* machining systems like milling machines/CNC, etc.



# 3D printing: limits

- any 3D printed object is an approximation, because of the digital-to-analog conversion (sampling problem) –*true for all 3DP technologies*:
  - limited precision and resolution
- physical limits (*related to the material/technology*):
  - non-isotropy of characteristics due to layering (e.g.: lower mechanical resistance along Z axis)

# Many 3DP technologies

A possible categorization by (raw) material:

- **powder** (self-supported, metal sintering, fast, cavities need holes, very expensive) (*inkjet+powder*)
- **liquid** (optical –high precision, light-controlled polymerization –special resins, expensive) (*inkjet*)
- **solid** (FDM, support is needed, pointed tips/cuspids are hard, wide choice of polymers, inexpensive)

# Professional 3D printers (10.000\$+)

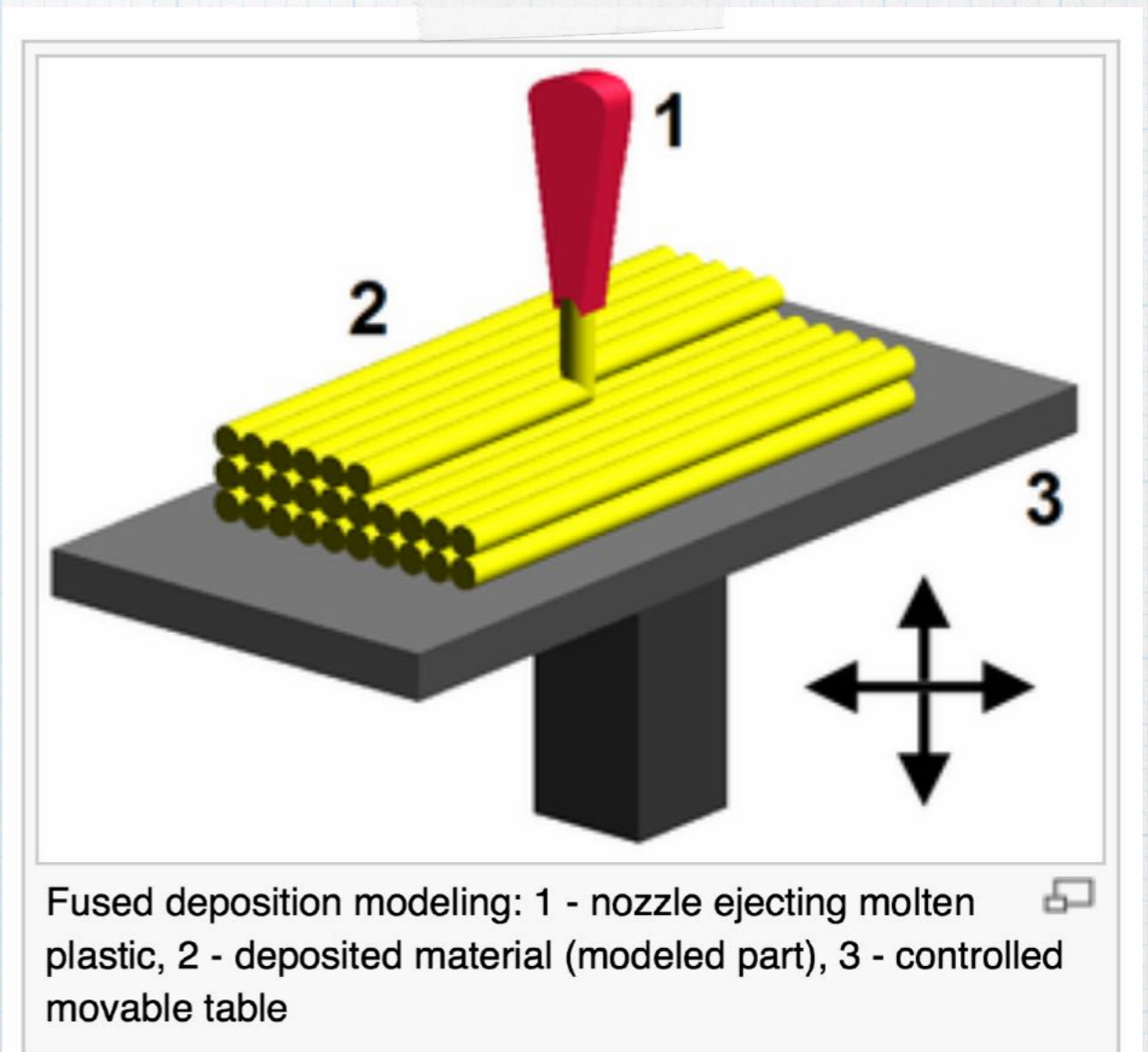
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- Pro 3D-printers can print objects
  - in plastic, starting from a filament (with FDM), or
  - in other material (like metals, ceramics, etc.) provided as powder and “assembled” by sintering (SLS)
  - and some are even able to print in full RGB color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



# Fused Deposition Modeling (FDM)

- The most affordable 3D printing technology is FDM: it uses molten plastic extruded through a nozzle. The nozzle or the object (or more often both) are moved along the three axes X,Y,Z.
- Also called FFF (fused filament fabrication).





Low-cost *personal*  
3D printers

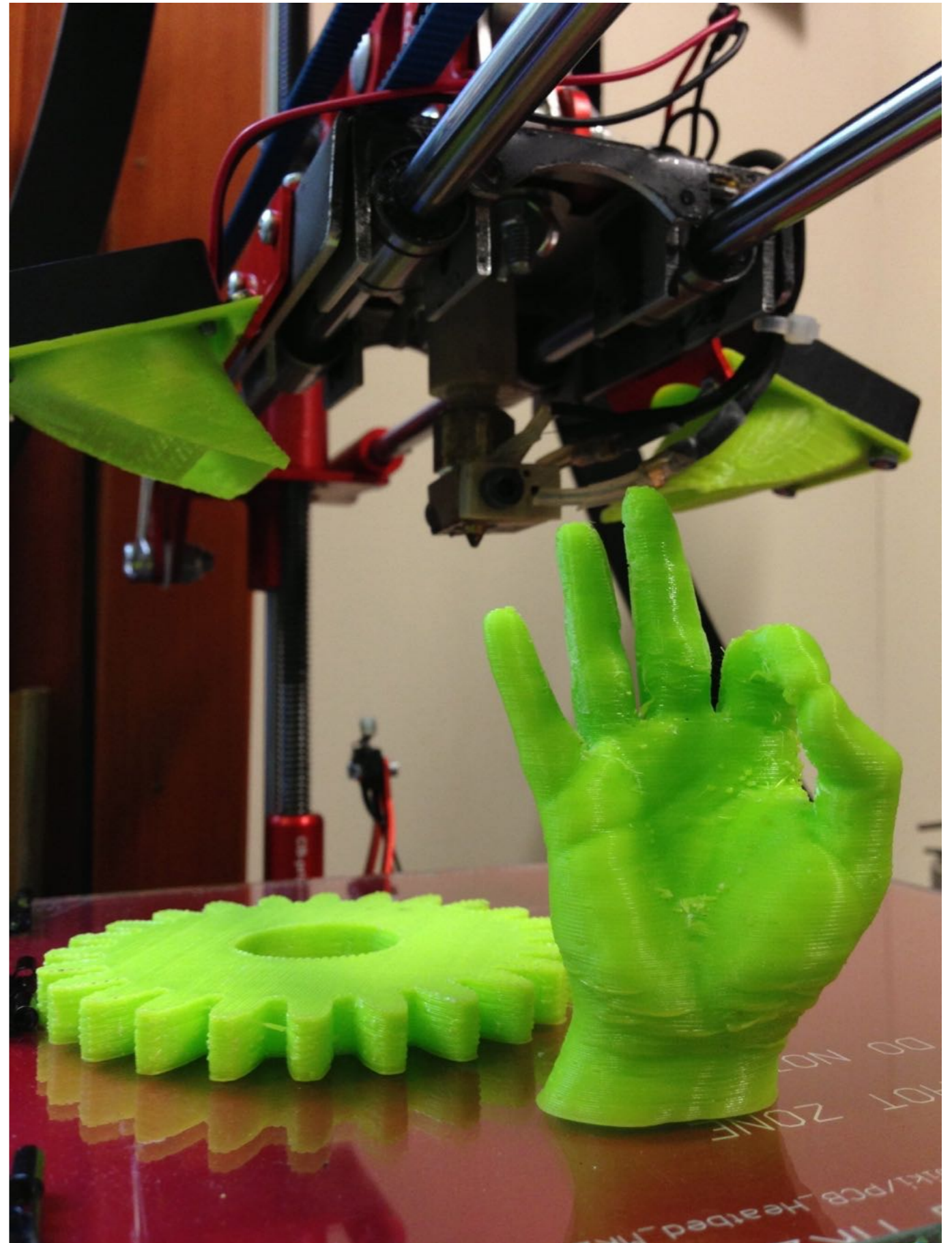
cost: from 300 to 3000 USD



# Open source + Open Hardware

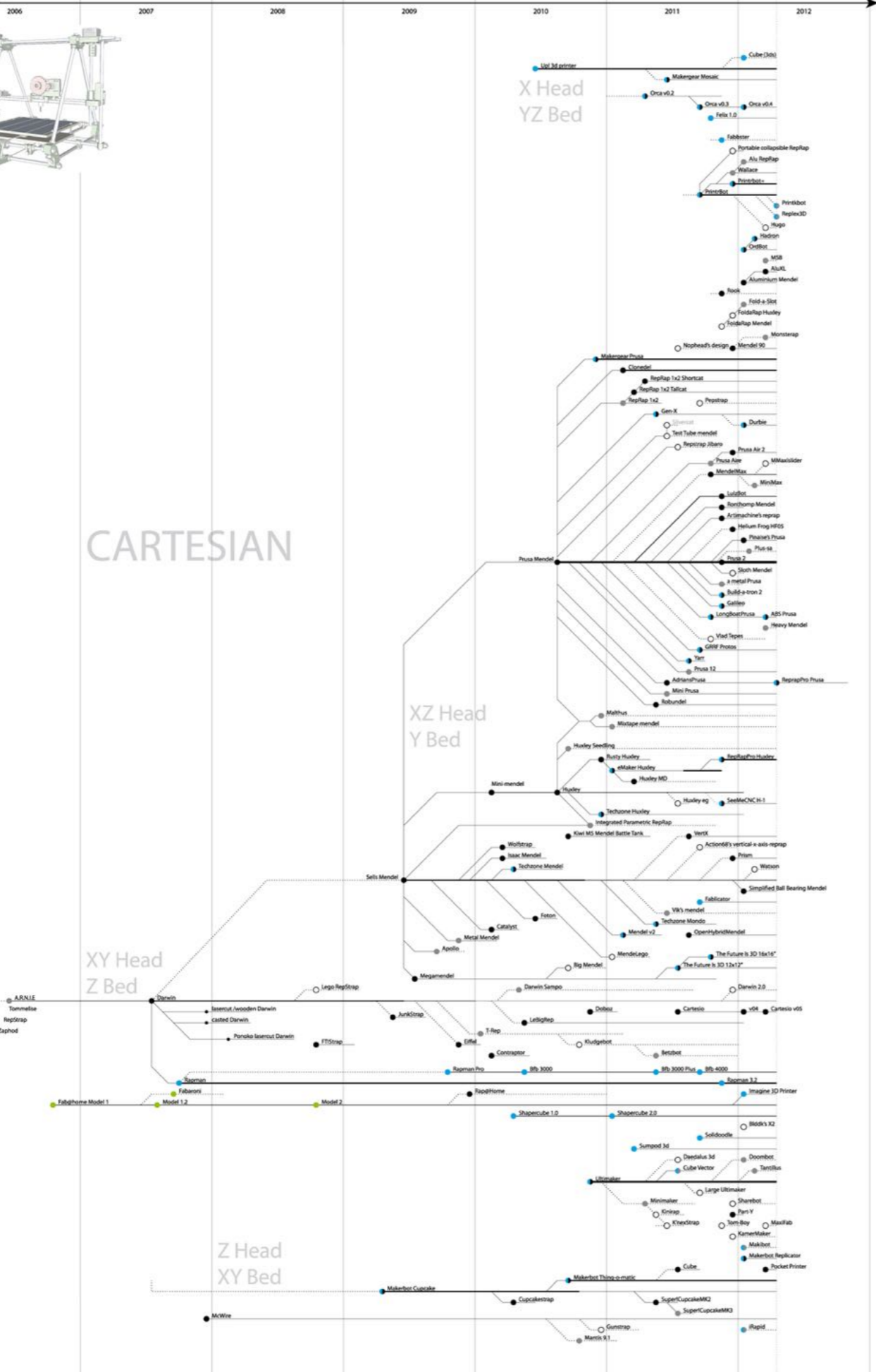
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- Low-cost printers use a plastic filament (ABS or PLA, 1.75 or 3mm thickness)
- Often hand-build, with plywood or acrylic frame and parts
- the software is free and mostly **open source**: 3D design apps, *slicers*, printer control apps, etc
- extensive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



# RepRap Family Tree

- Working
- Experimental
- Concept
- Other other project
- Commercial
- Common
- - - Less common
- - - Work in progress



CARTESIAN

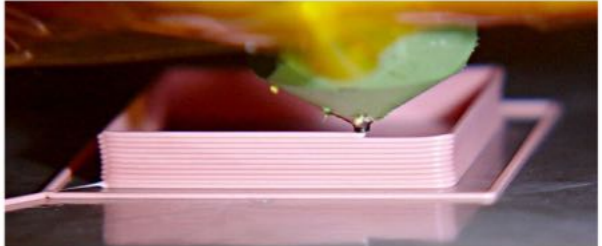
XZ Head Y Bed

XY Head Z Bed

Z Head XY Bed

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## DIY 3D Printing Mechanics



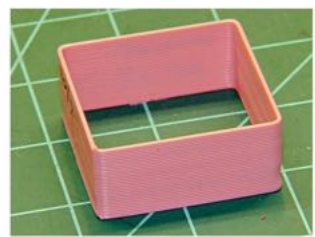
- Building things with a hot-melt glue gun
    - A very **small** glue gun: nozzle 0.2 to 0.6 mm dia
    - A very **hot** glue gun: 190 to 230 °C = 350 to 450 °F
- <http://www.thingiverse.com/thing:2064>

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## Cartesian Coordinates

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



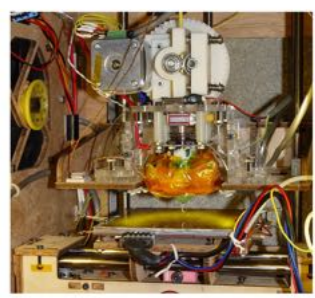
<http://www.thingiverse.com/thing:2064>

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## 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!

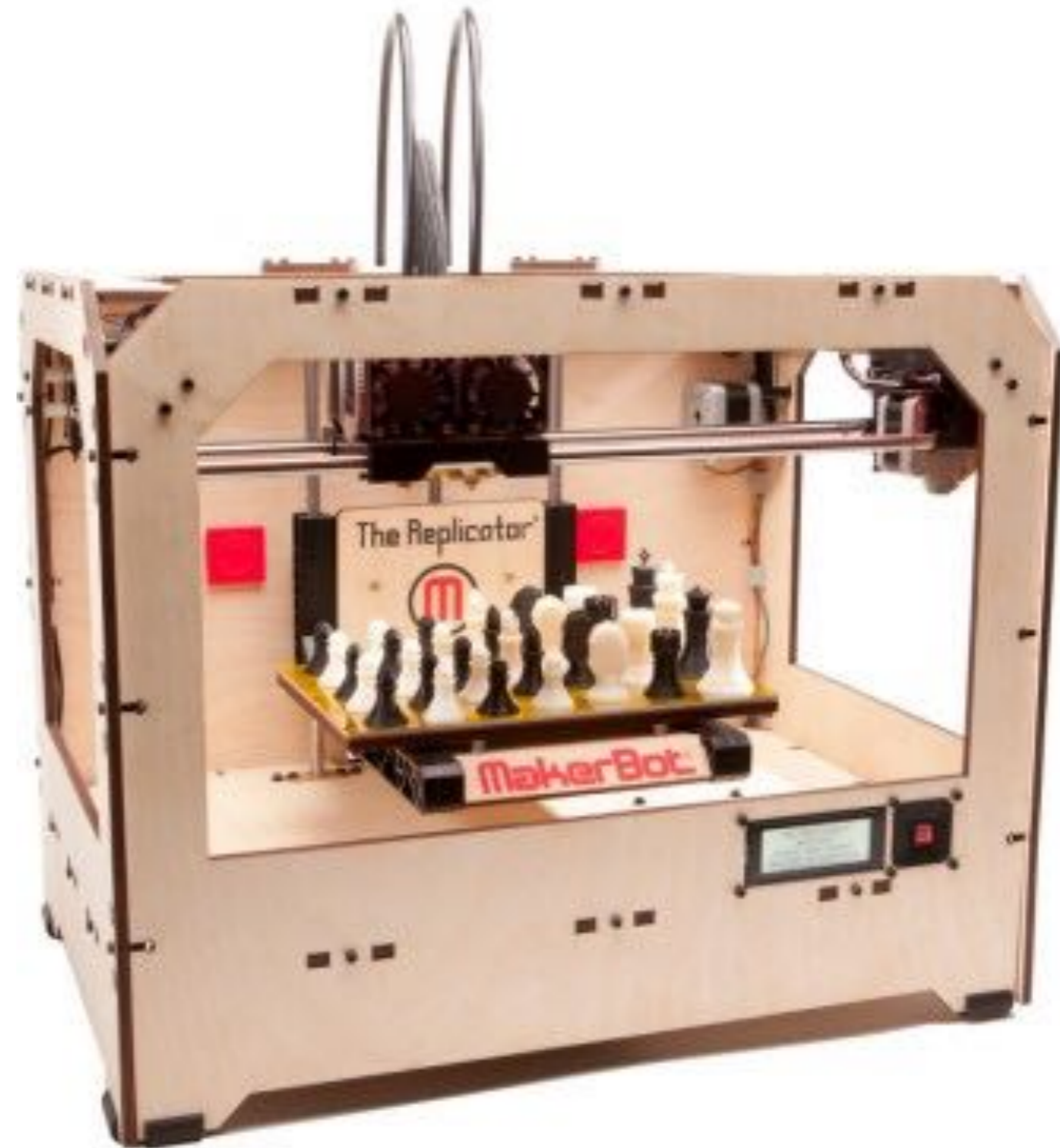


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# Makerbot Replicator

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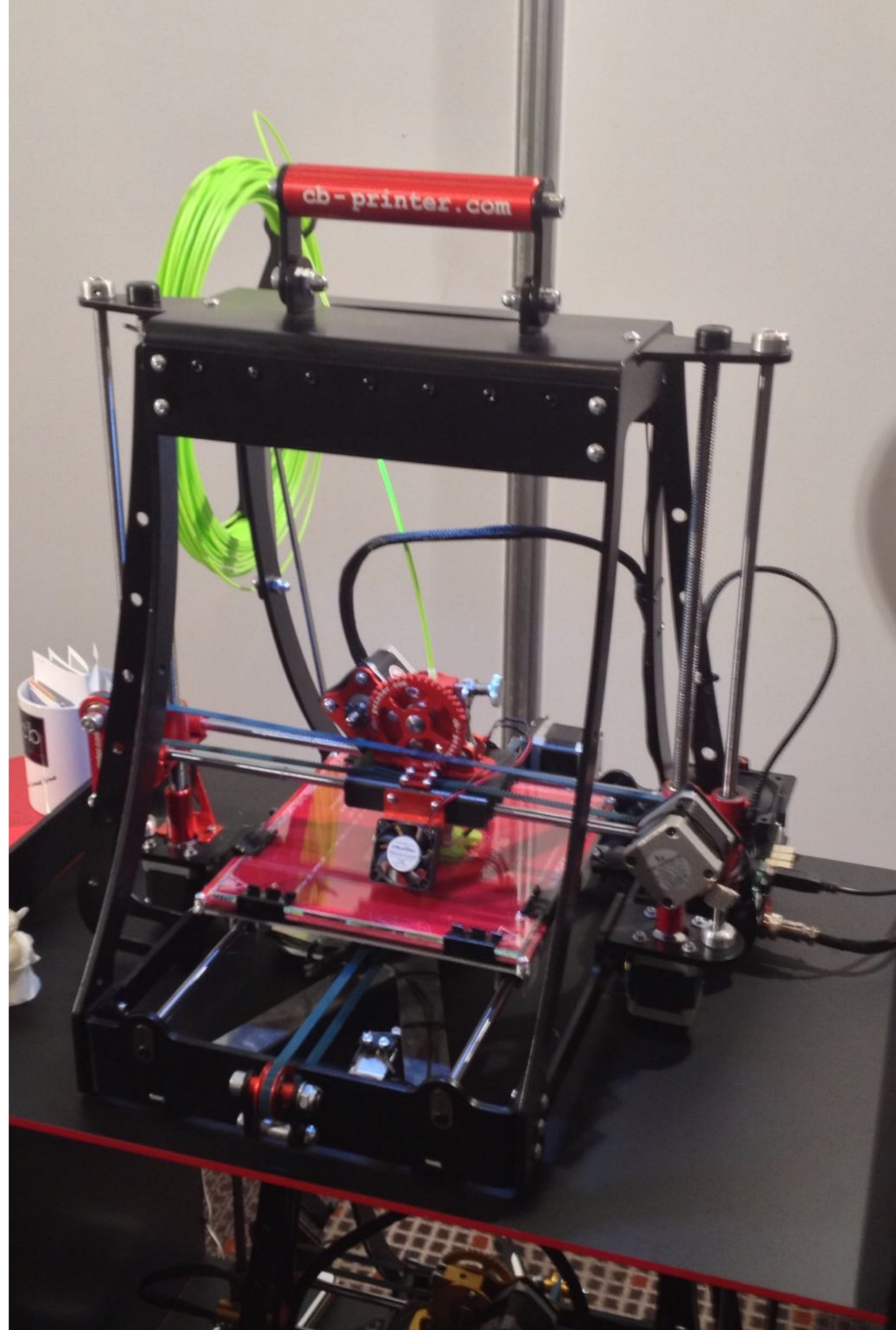
- Third generation printer (the first two were the *Cupcake* and the *Thing-o-Matic*)
- Single or *Dual head* (can print in two colors, or two plastic types)



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

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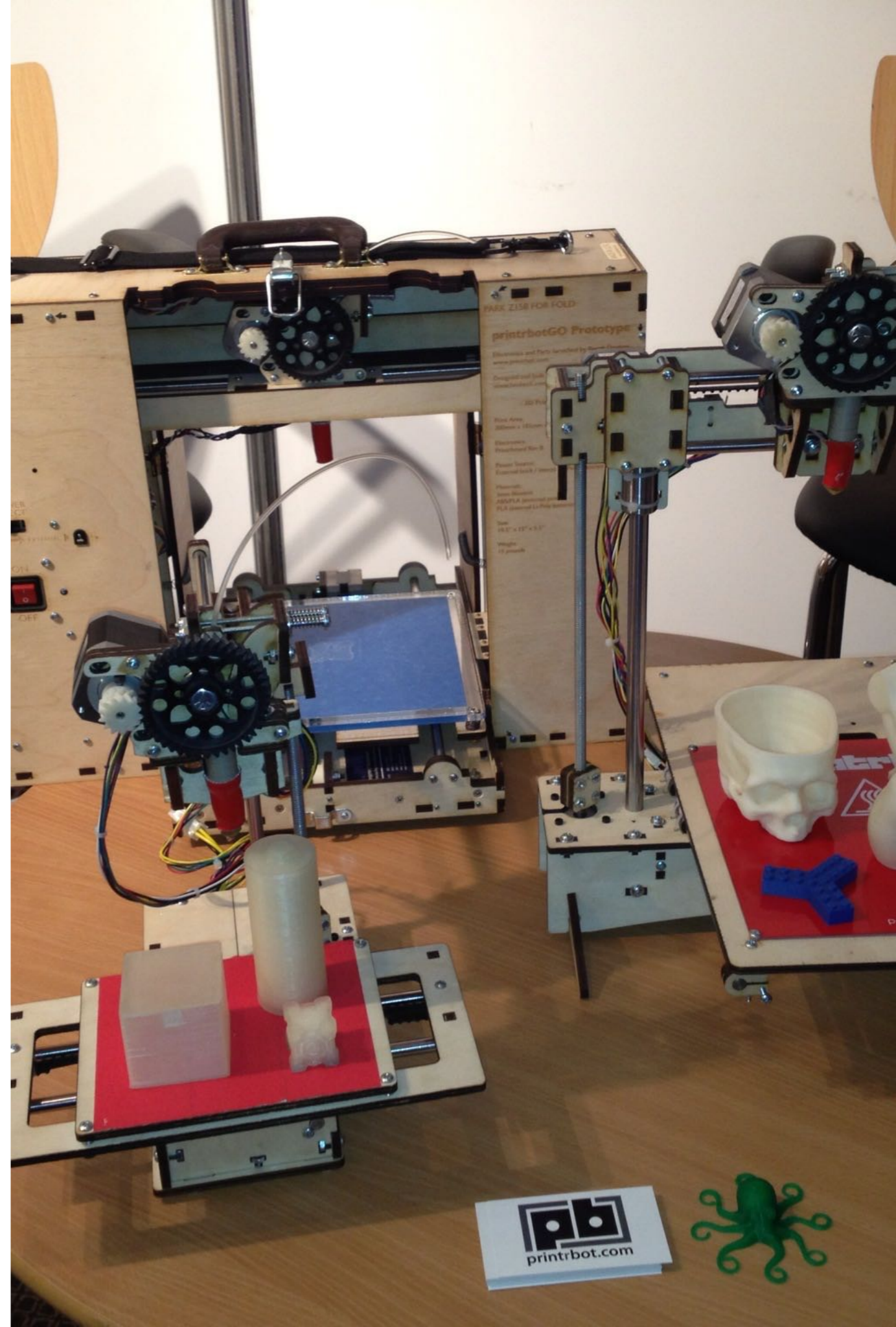
- Many variations on the theme
- Mostly designed (and marketed) by members of the hacker community in US and Europe
- Everything is open, you can buy or build/modify them



# Printrbot

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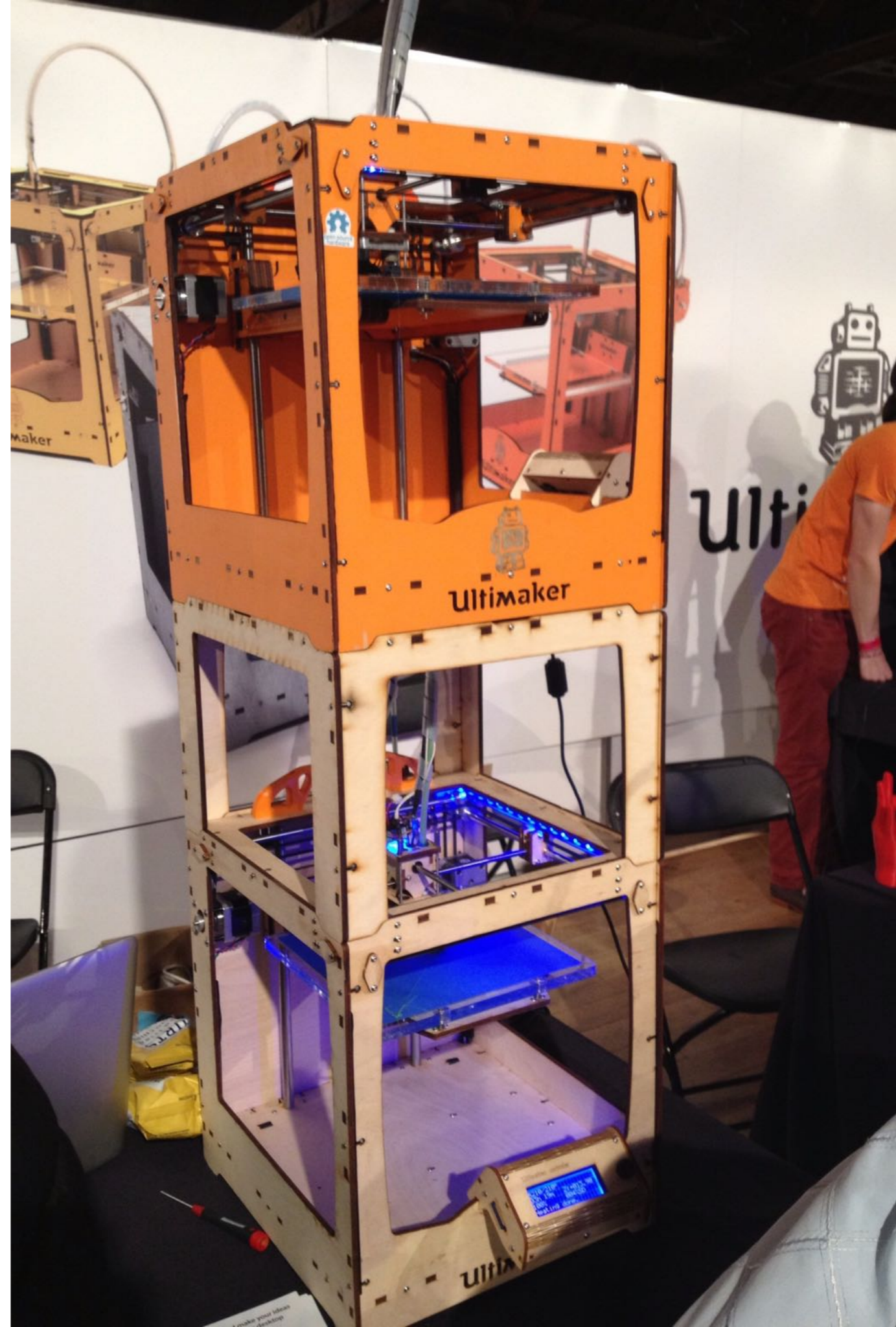
- These are *very portable* models, even battery powered. Mostly designed for education (school), available from the U.S. Cost: starting from ~400\$



# Not only from U.S.: the Ultimaker

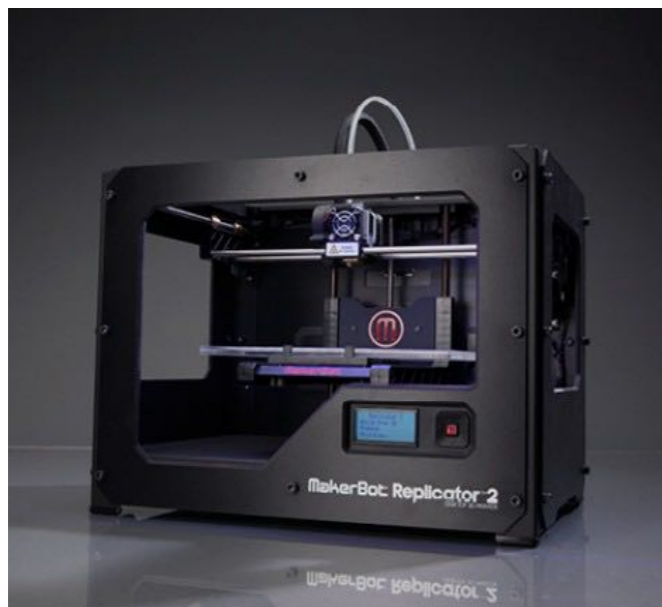
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- Developed in the *Netherlands* by a student (as a byproduct of his MSc thesis)
- Cost: €1000 as kit, fully open source



# 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)



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My Cart (0)

## Cube<sup>®</sup>

### A 3D Printer for you.

Express yourself in 3D.  
Easy to use.  
Only \$1299

Order now



What you can do with your Cube

#### Get Print Files Online

Then print them on your Cube

Shop now

#### Customize Online with Free Apps

No design skills required.

Try it now

#### Create Anything

Use Cubify Invent (or other software) to design your creation

Learn more

## Features

Activate my Cube Download Cubify Client Software Tech Specs

#### Plug and Play Simplicity

Straight out of the box - no assembly required

Learn more

#### Print in Vibrant Colors

Bright colors for your bright ideas.

Learn more

#### 25 Free Creations

Ready to print Creations made by top designers

Learn more

# The Cube (\$1299)

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# And many more...

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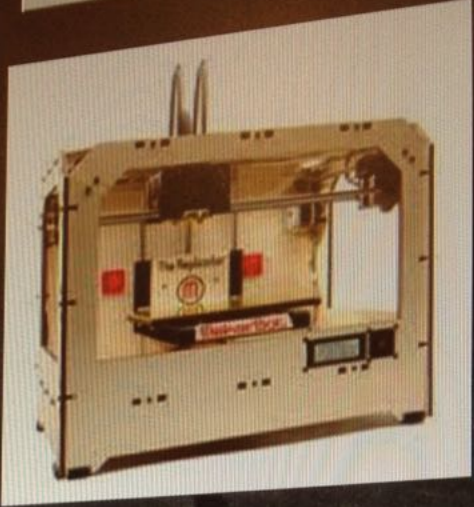
- Different solutions
- Different level of skills required to operate
- Different prices
- Different philosophies
- The market is still growing quickly and searching an equilibrium...

The screenshot shows a software interface for 3D printing. It features two main panels, each with a table of metrics and a printer image. The top panel is for a MakerBot Replicator, and the bottom panel is for a 3D Systems Cube. Both panels include 'End Preheat' and 'End Print' buttons.


### MakerBot Replicator

Predicted time	
Predicted Cost	
Current time	00:39:43
Current Cost	£0.4229
Co2 (g)	103.2
Co2 	129.04%
Co2 	60.72%
km 	86.75%


End Preheat    End Print



### 3D Systems Cube

Predicted time	
Predicted Cost	
Current time	00:39:43
Current Cost	£0.0007
Co2 (g)	0.4
Co2 	0.47%
Co2 	0.22%
km 	0.31%

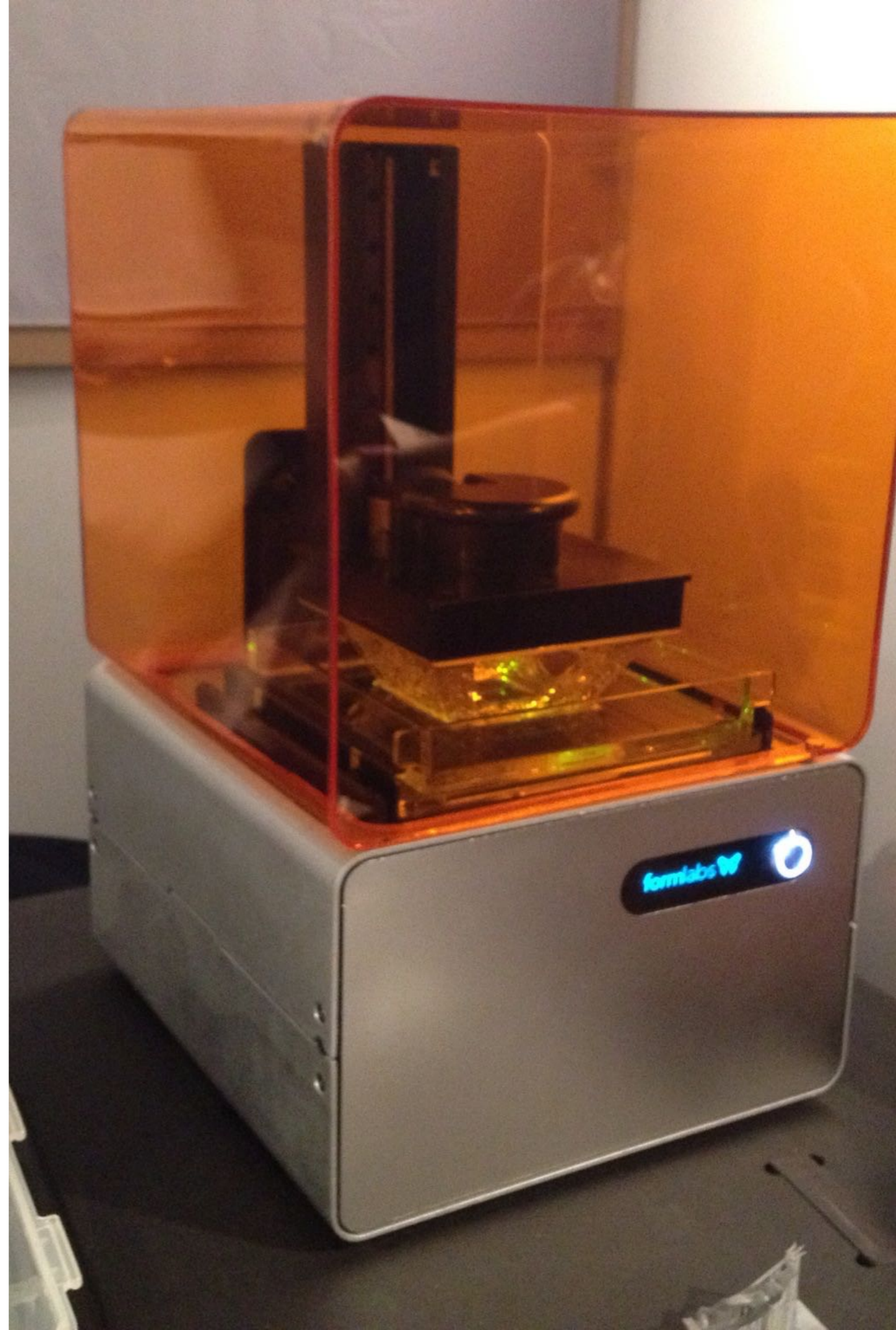
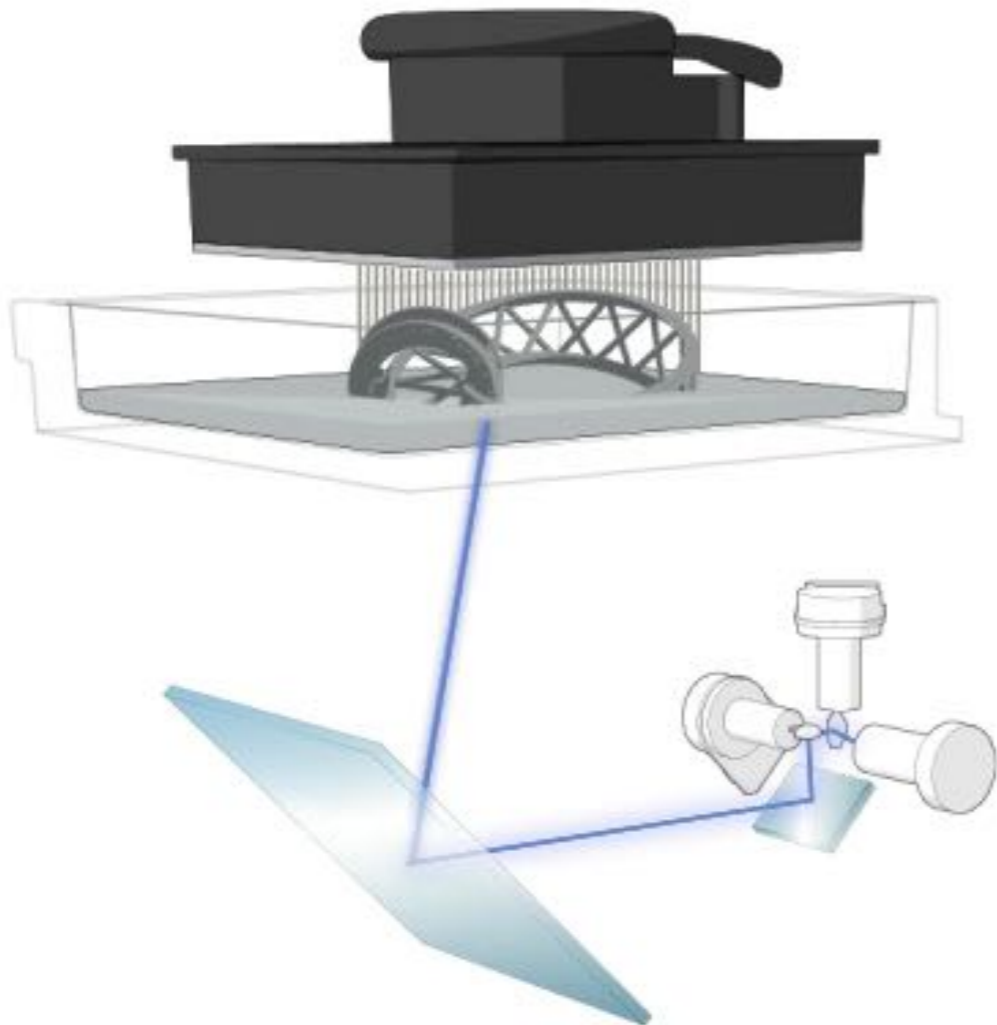
End Preheat    End Print



# 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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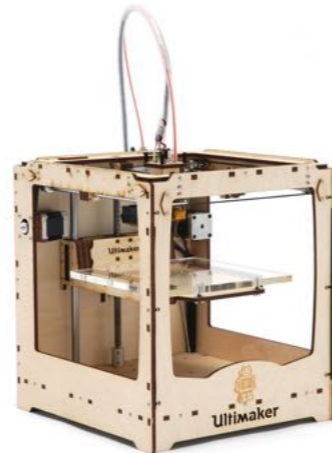
Pro only



first personal  
(for hackers)

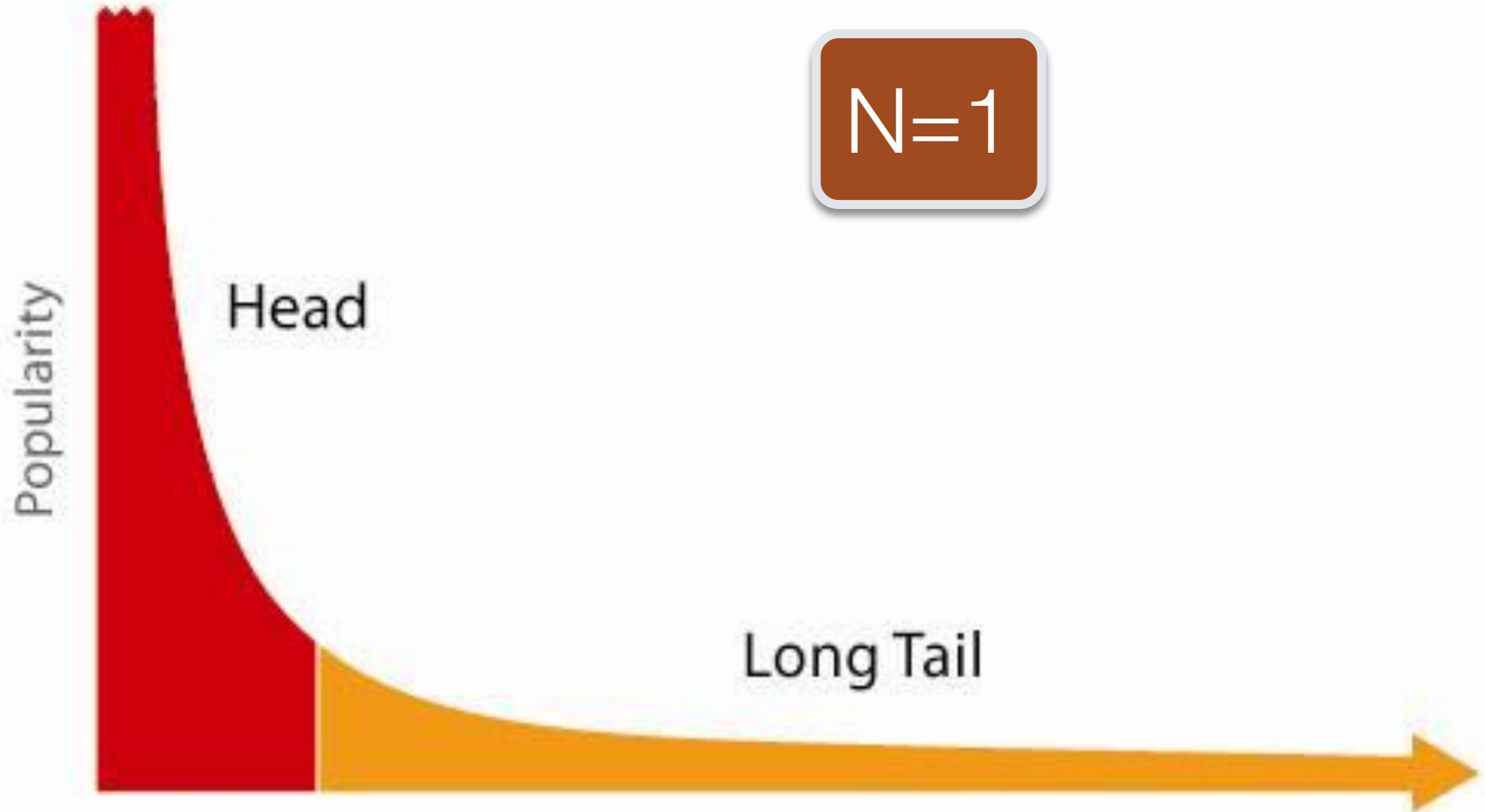


really personal  
(mass produced)



?

???



*La coda lunga*

by Chris Anderson

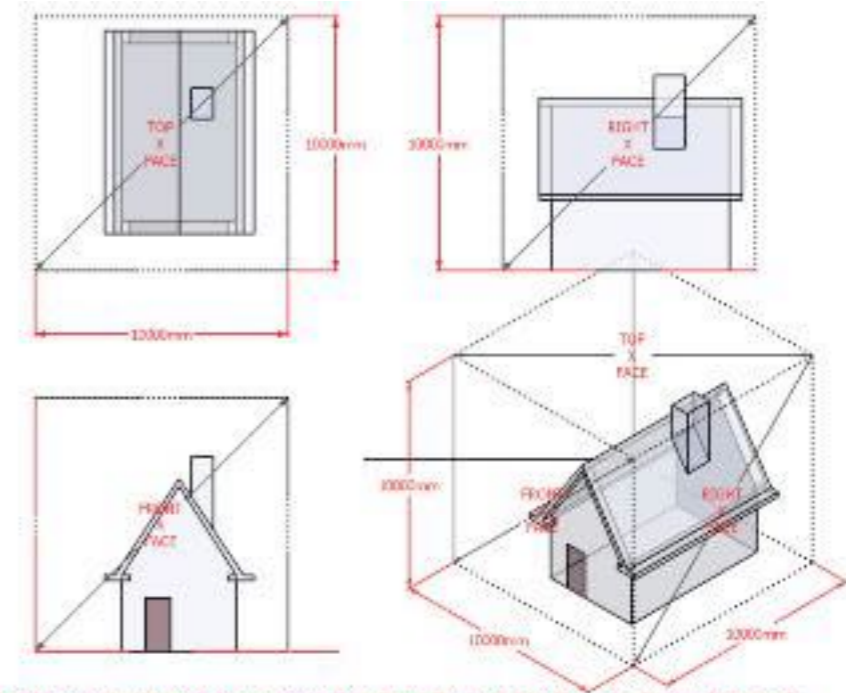


HOW TO print an object?

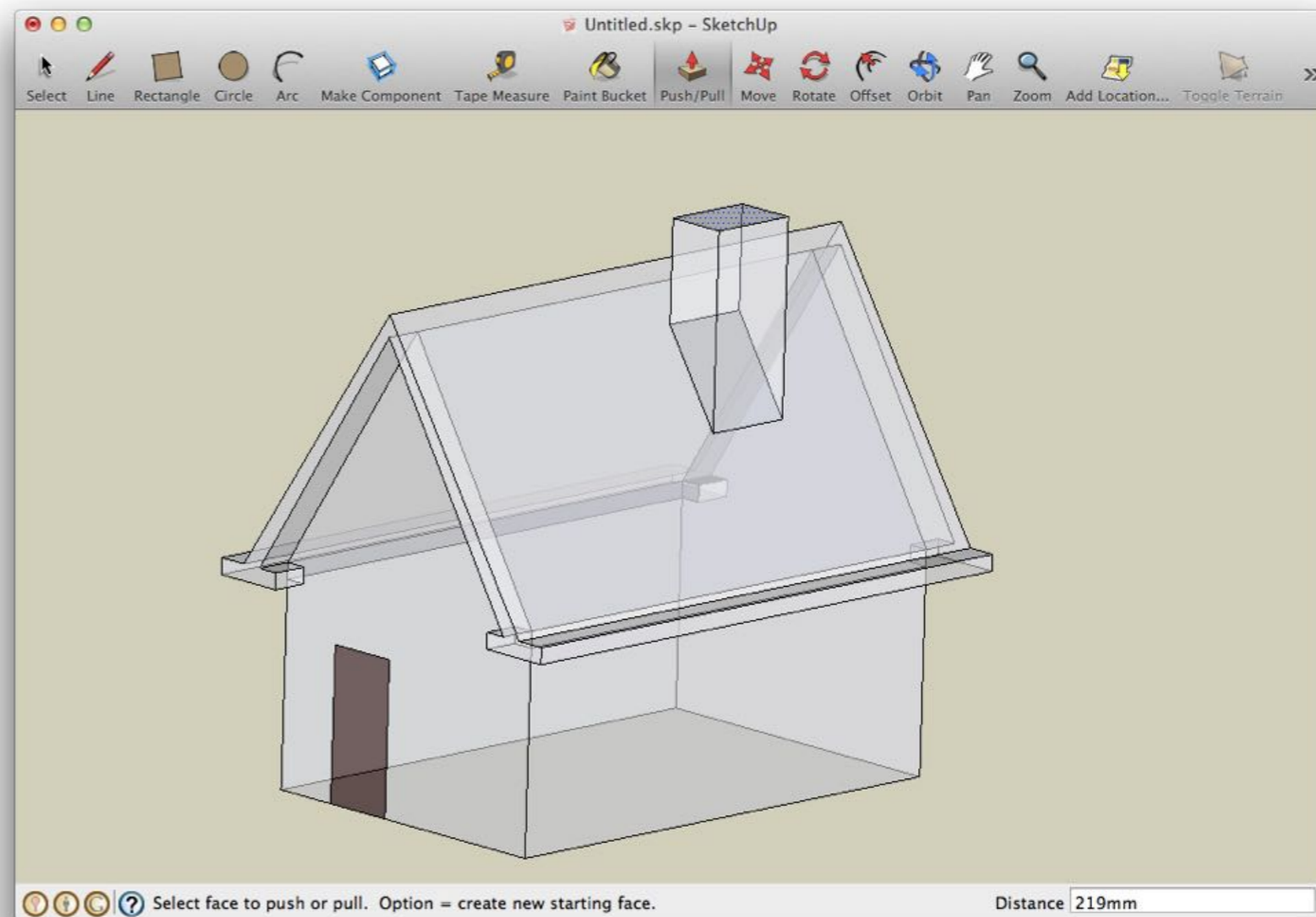
...practical 3D-printing for beginners

# #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...

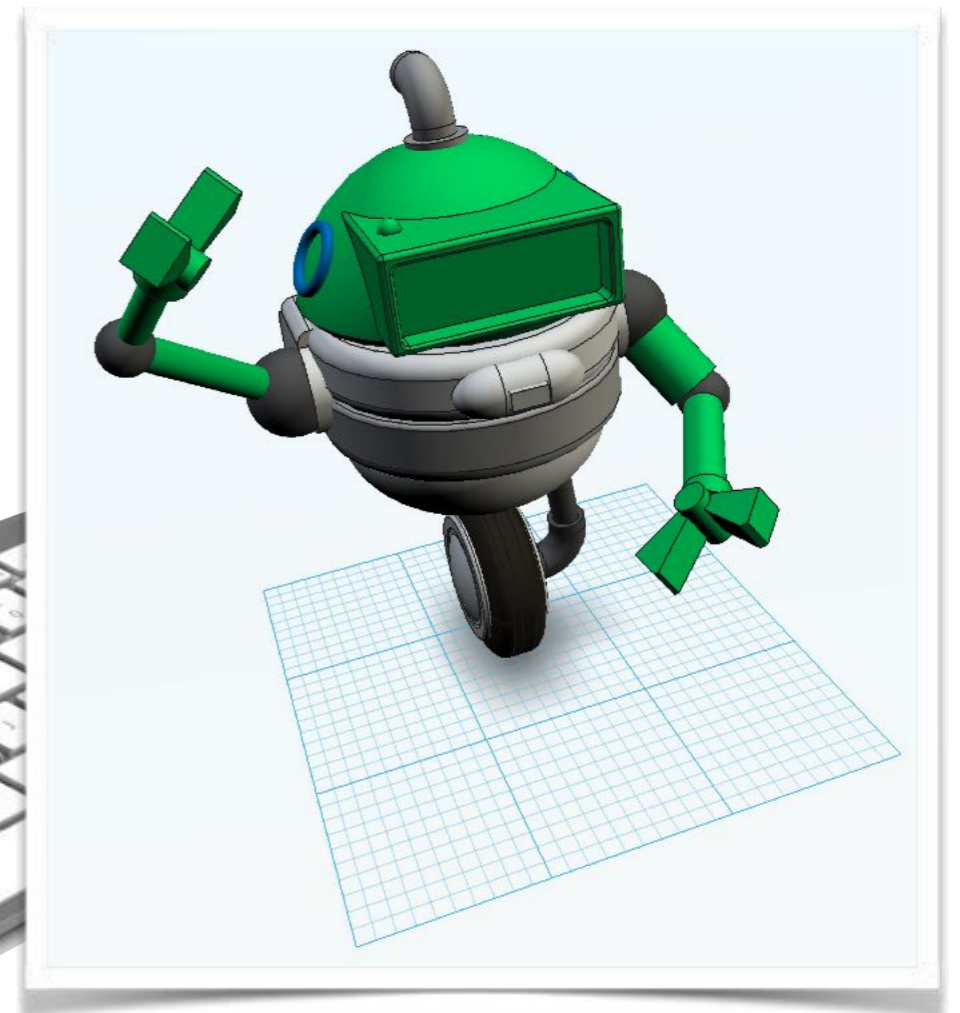


Always work within editing context of the component Boundaries. Standard\_Box to update all views (=scene 4)  
(dashed lines and red measures are just for informative reasons and may be deleted from the component)






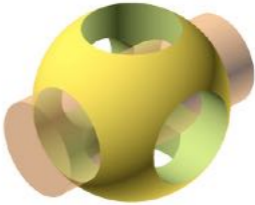
# 3D modeling

- Going from an idea to a geometrical (or functional) model, there may be multiple steps:
  - Draft shape (quick, intuitive)
  - Precise dimensions (numerical input)
  - Parametric model (what-if modeling)



# 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...



# 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)

**nervous system**

Cell Cycle WebGL design app

CREATE YOUR OWN 3D-PRINTED JEWELRY. PLAY WITH AN INTERACTIVE PHYSICS SIMULATION TO FORM UNIQUE CELLULAR DESIGNS.

**BASIC STRUCTURE**

2-LAYER  1-LAYER

HORIZONTAL CELLS  REBUILD

VERTICAL CELLS  
inside  outside

**SIZING AND STYLING**

CHOOSE A SIZE DIAMETER 71.3 mm  
custom

ROUNDNESS  
inside  outside

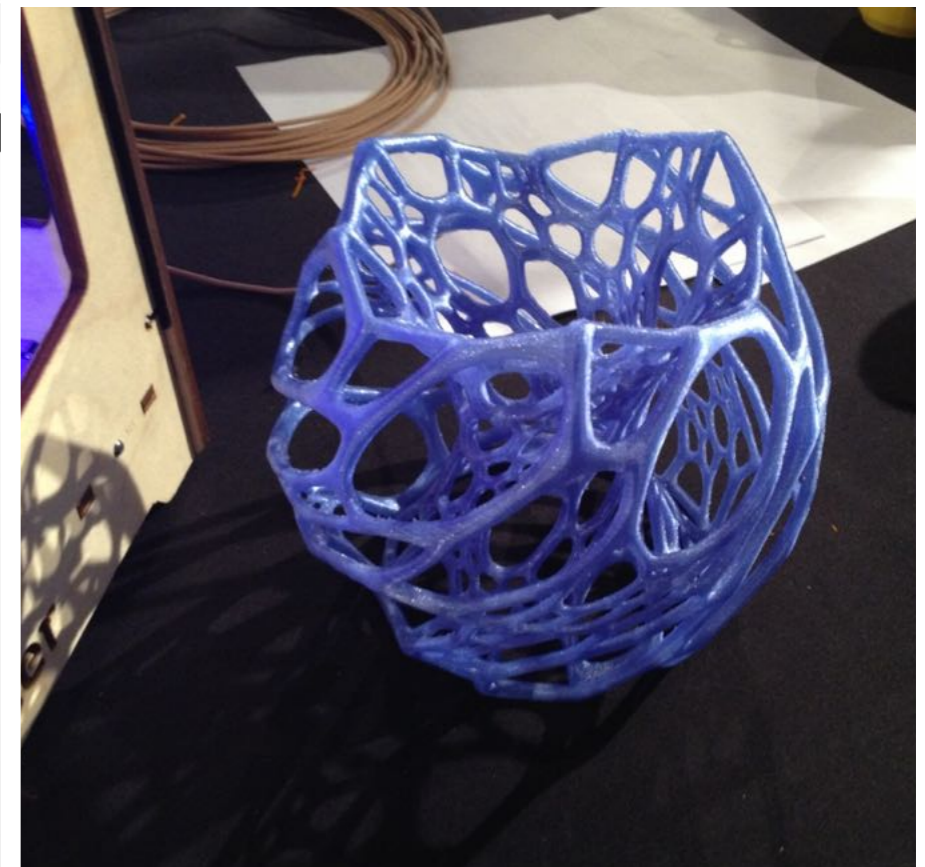
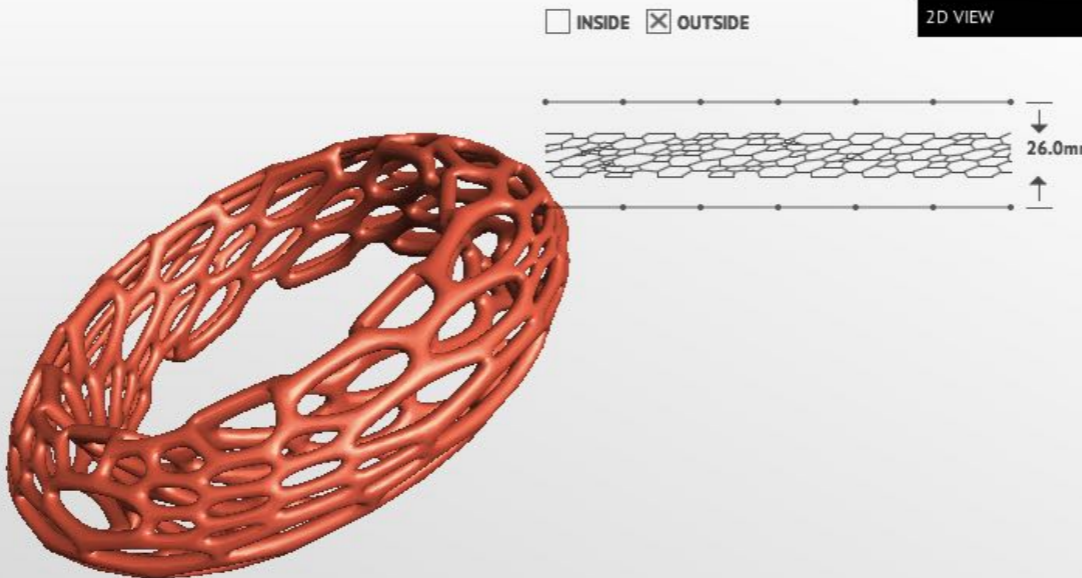
THICKNESS 2.9 mm TWIST

**FINALIZE AND PURCHASE**

CHOOSE A MATERIAL PRICE  
red nylon \$78 ships in 3 weeks

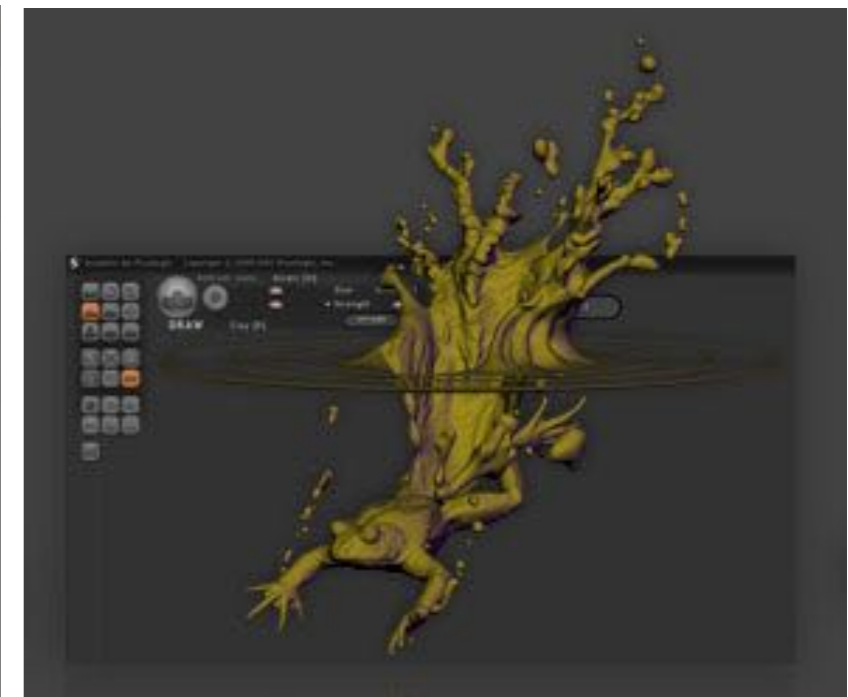
help login cart: 0 items

INSIDE  OUTSIDE 2D VIEW



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

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



## 123D Catch

Capture places, people and things in 3D using your iPad or iPhone. Share your catches, or 3D print a real object!



## 123D Circuits

Design, compile, and simulate your electronic projects online.



## 123D Creature

Have a perfect character idea in your head? Bring it to life with this free app for iPad!



## 123D Design

123D Design is a free, powerful yet simple 3D creation and editing tool which supports many new 3D printers.



## 123D Make

Turn your amazing 3D models into even more amazing do-it-yourself projects. Download the free app now.



## Meshmixer

Meshmixer is the ultimate tool for 3D mashups and remixes. Mash, mix, sculpt, stamp or paint your own 3D designs.



## 123D Sculpt

Push, pull, pinch, paint, smooth, tug. More fun than a Renaissance studio, cleaner than clay.



## Tinkercad

Get started with basic 3D modelling – no downloads required.



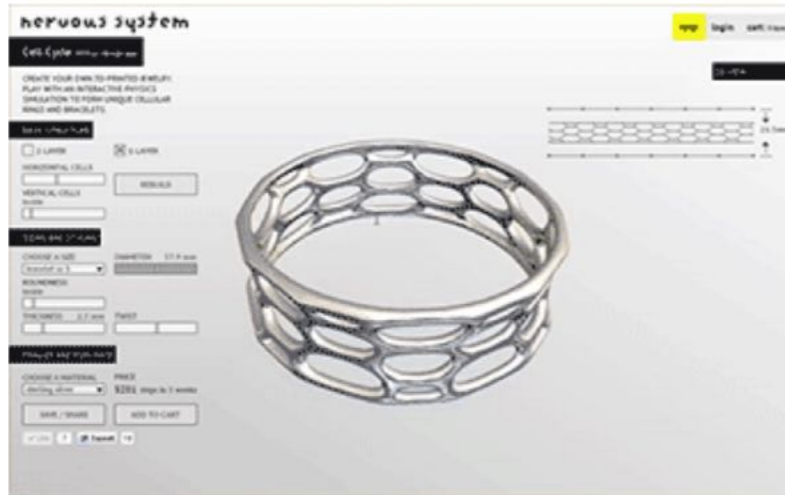
## The Sandbox

Here you'll find some technology in progress – this is stuff we're working on or experimenting with.

# apps

generative design apps you can use online to design your own products

## CELL CYCLE



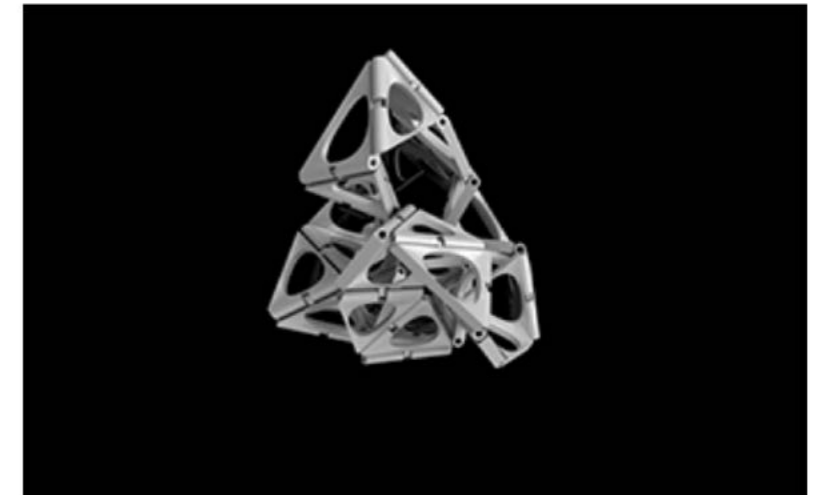
sculpt 3D-printed jewelry inspired by cellular structures

## GENERATIVE JIGSAW PUZZLE



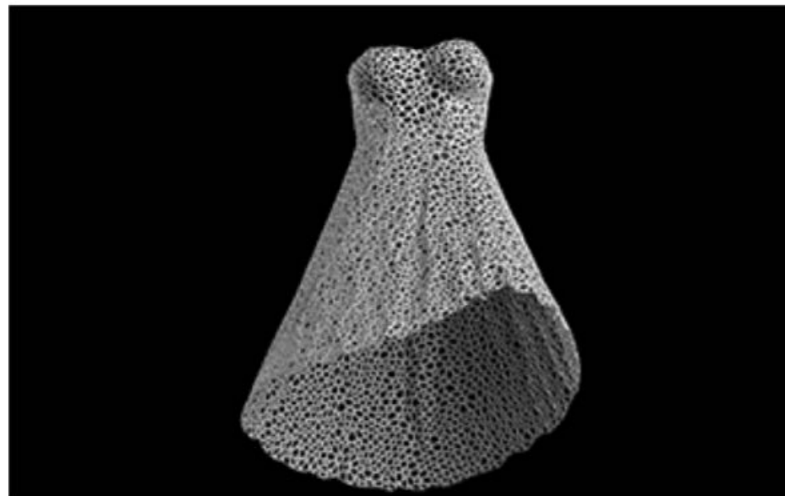
lasercut wood jigsaw puzzles from your art

## KINEMATICS



complex, foldable 3D-printed jewelry

## KINEMATICS CLOTH



custom-fit 3D-printed clothing

## KINEMATICS@HOME

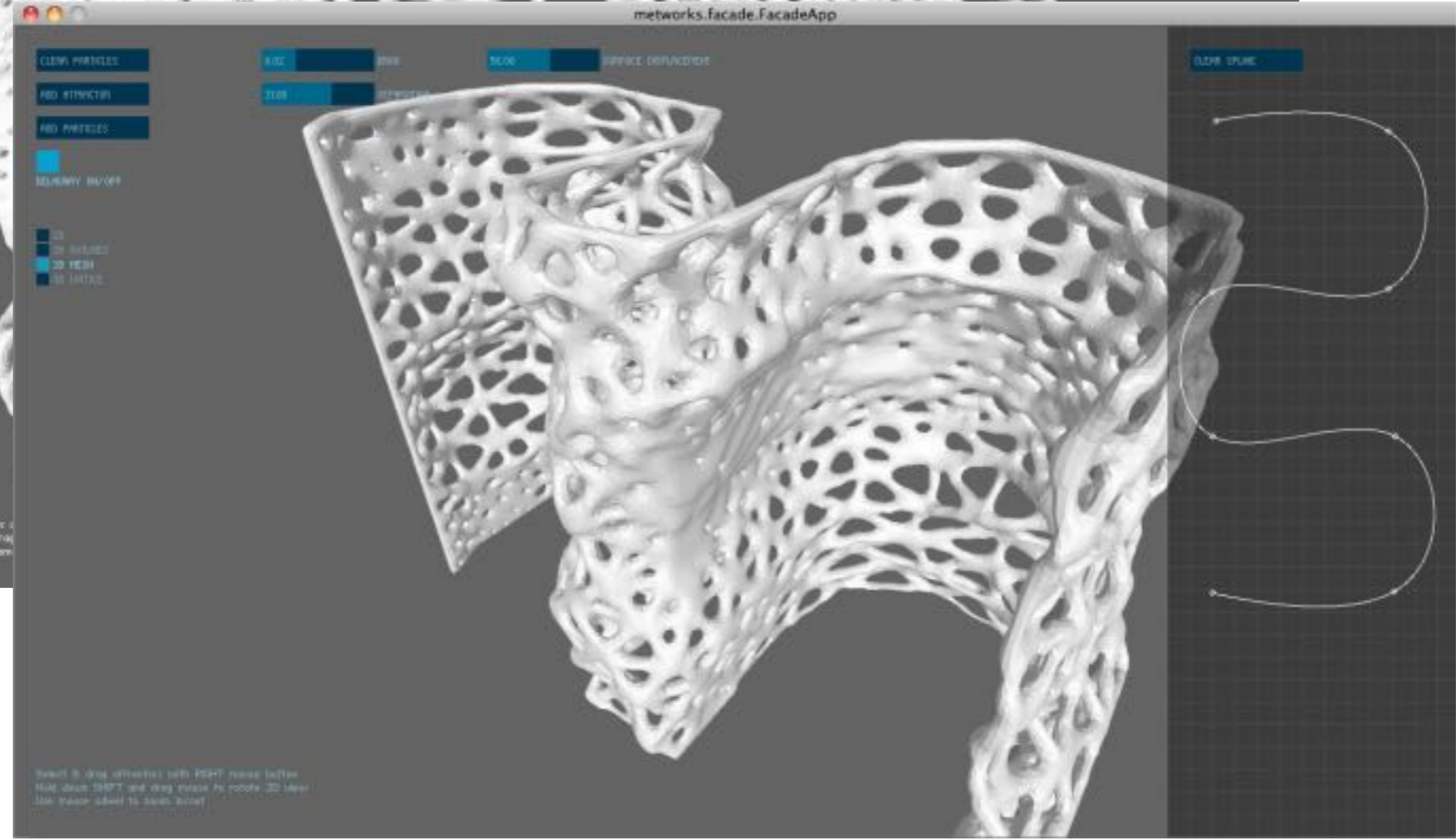
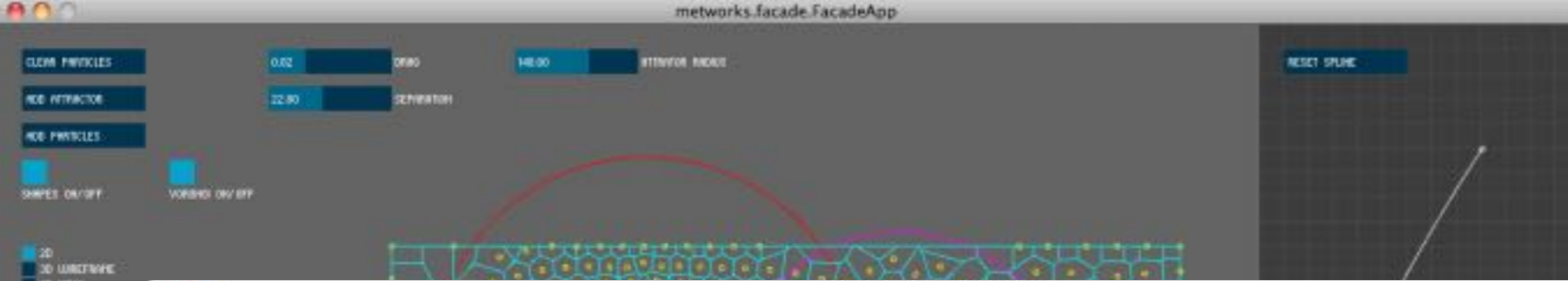


custom-fit, flexible jewelry to 3D print at home

## RADIOLARIA



delicate stainless steel jewelry created in a simulation of a spring mesh



Select & drag attractor  
Hold down SHIFT and  
Use mouse wheel to z

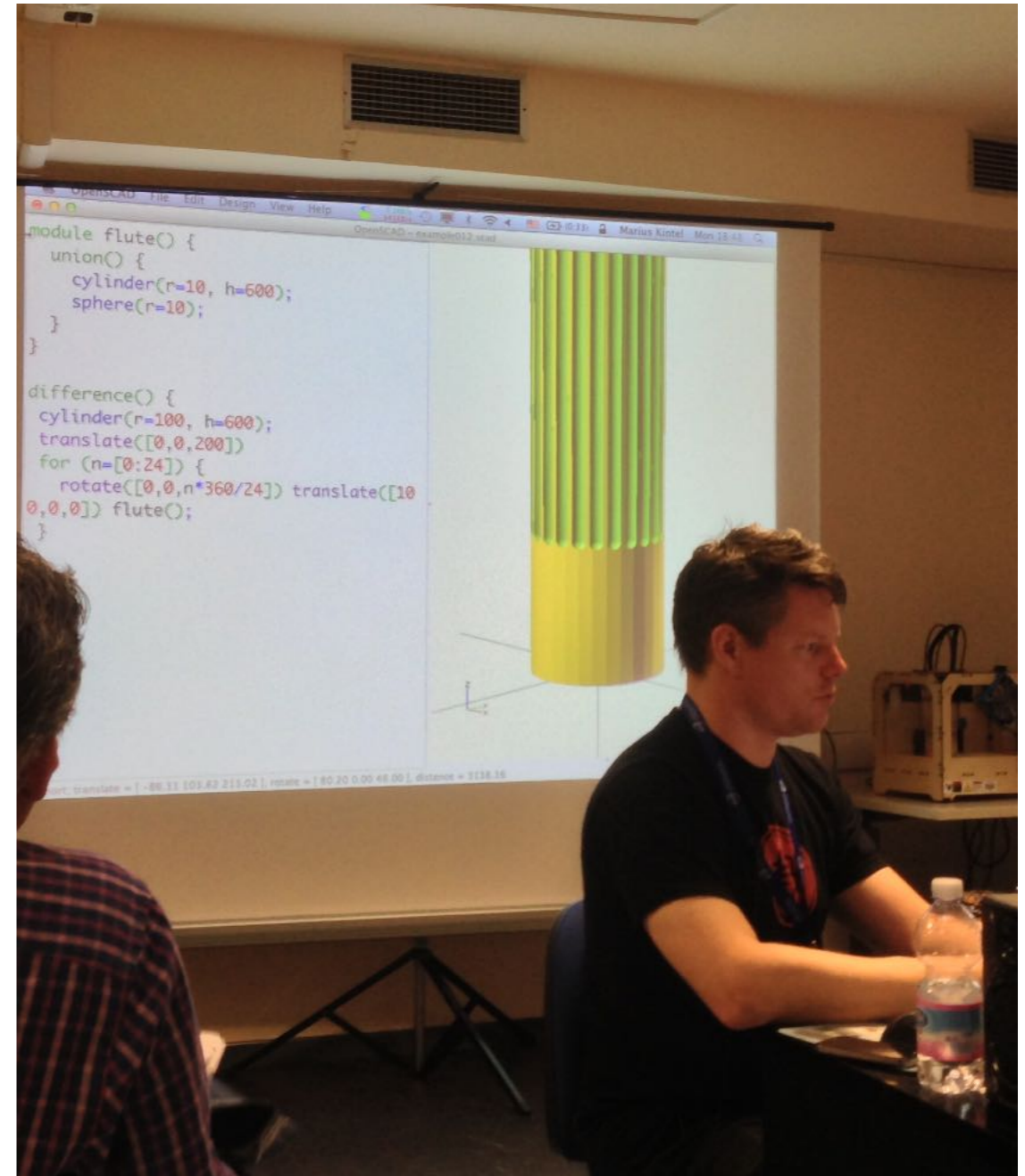
Select & drag attractor with  
Hold down SHIFT and drag on  
Use mouse wheel to zoom in!

Select & drag attractor with  
Hold down SHIFT and drag  
Use mouse wheel to zoom

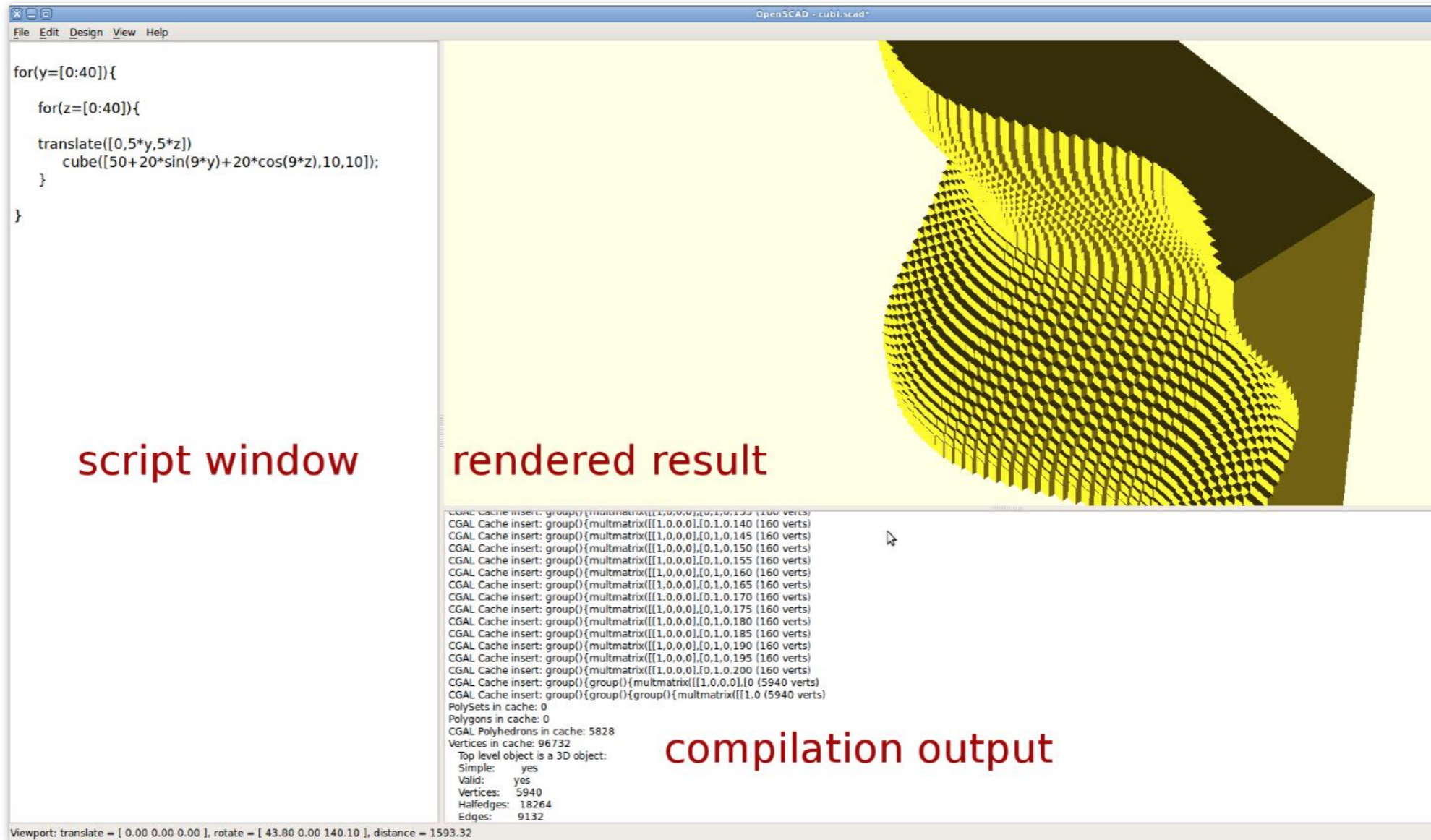
Select & drag attractor with RIGHT mouse button  
Hold down SHIFT and drag mouse to rotate 3D view  
Use mouse wheel to scroll wheel

# OpenSCAD

- OpenSCAD is a programming language for for creating solid 3D CAD models
- it's free, multiplatform (Win, OS X and Linux) and opensource, the lead author is Marius Kintel (see photo ;-)
- web: [openscad.org](http://openscad.org)



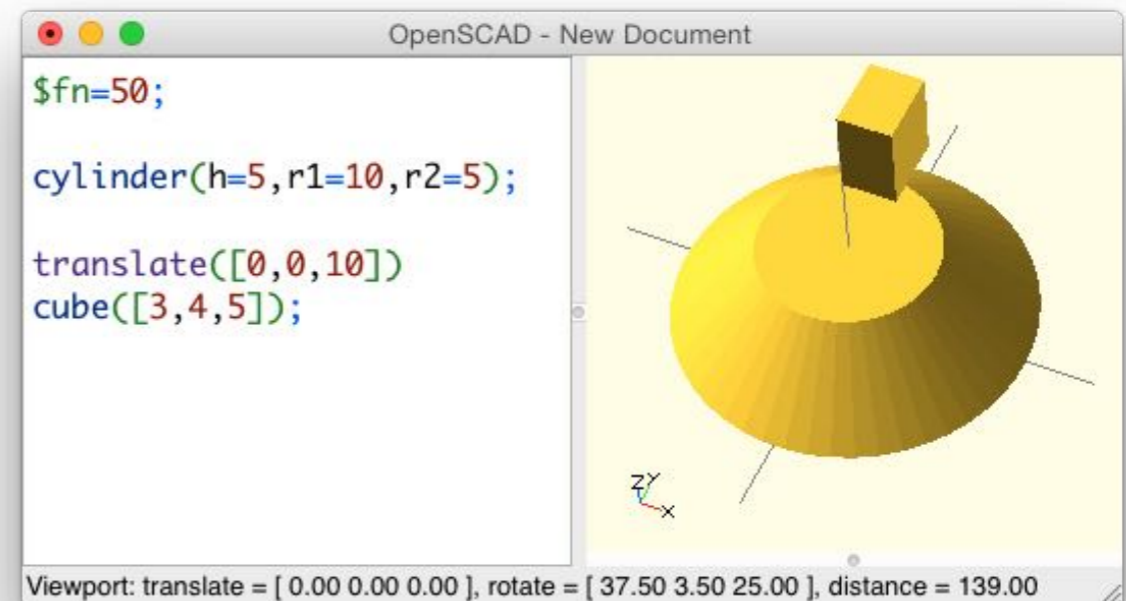
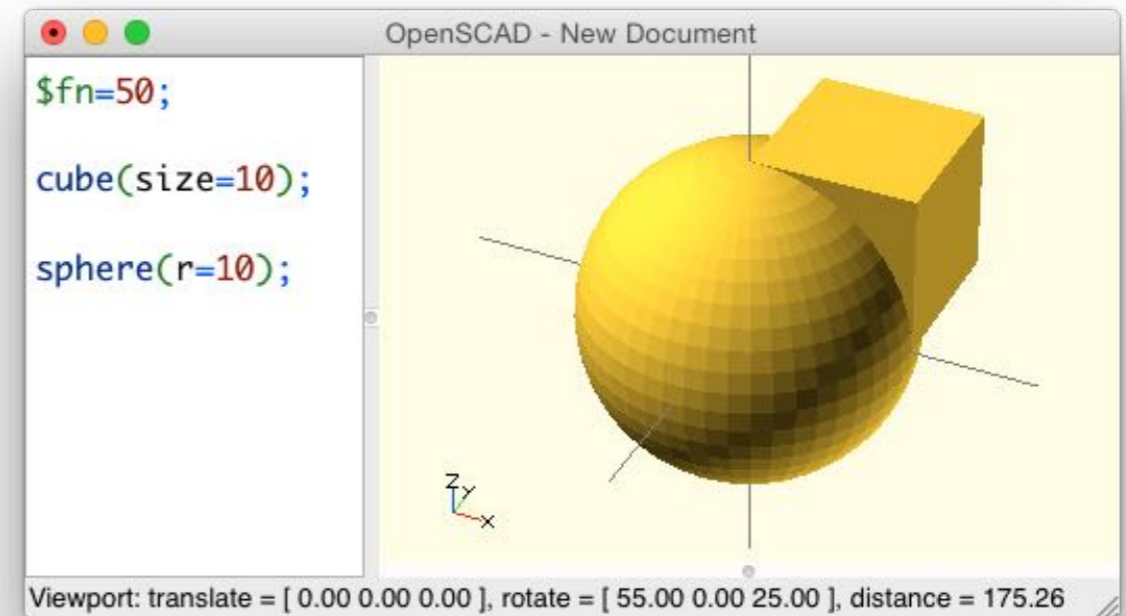
# OpenSCAD interface



*To render:* menu Design > Compile and Render (F6)

# 3D primitives

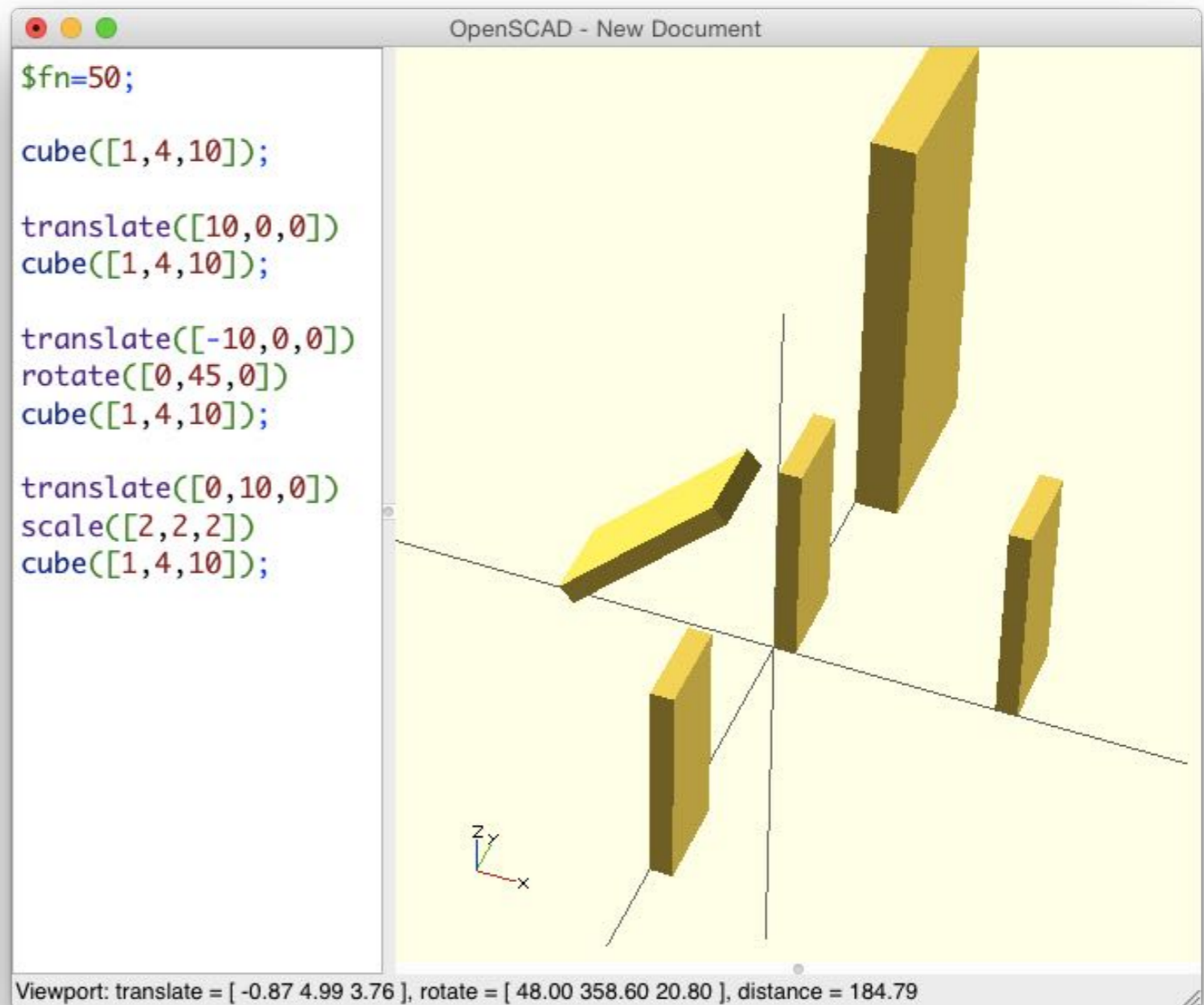
- **cube** ( *size=10* ) ;
- **sphere** ( *radius=10* ) ;
- **cylinder** ( *h,r1, r2* ) ;
- cube ( [*width, height, depth* ] ) ;
- polygon ( [*points*] ) ;





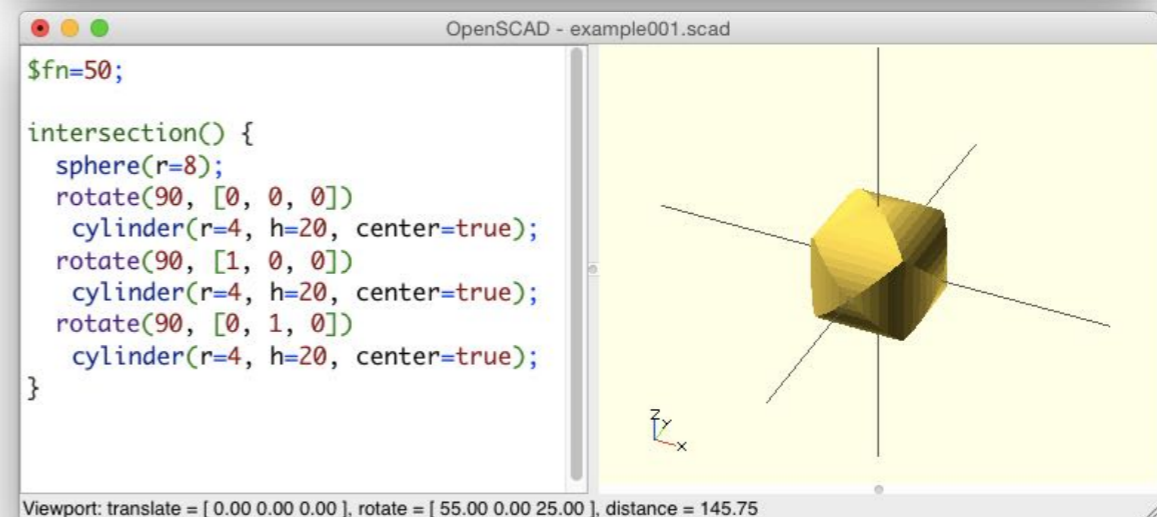
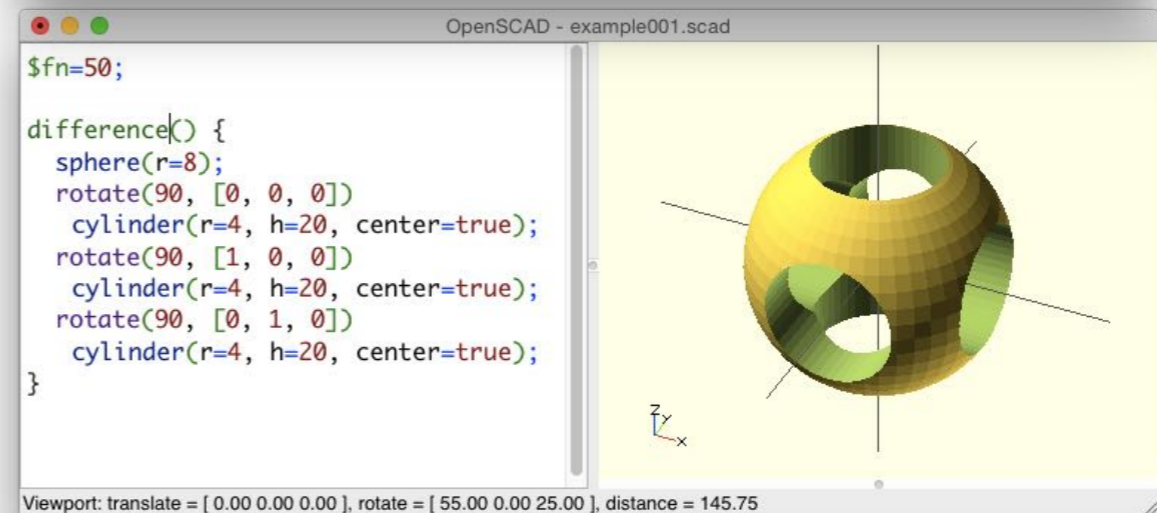
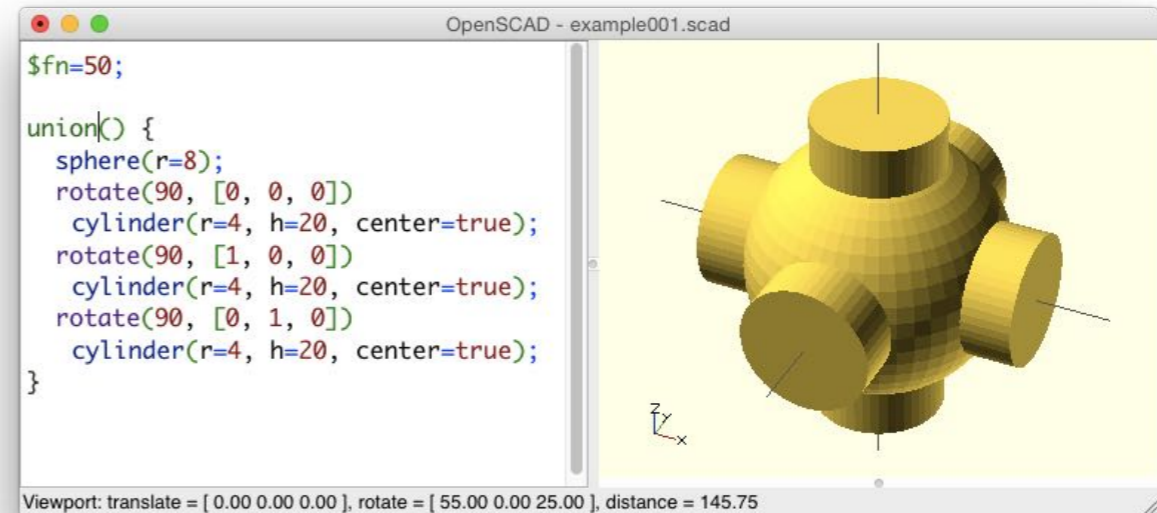
# Transformations

- translate ( $[x,y,z]$ ) primitives ;
- rotate ( $[x,y,z]$ ) primitives ;
- scale ( $[x,y,z]$ ) primitives ;
- mirror ( $[x,y,z]$ ) primitives ;



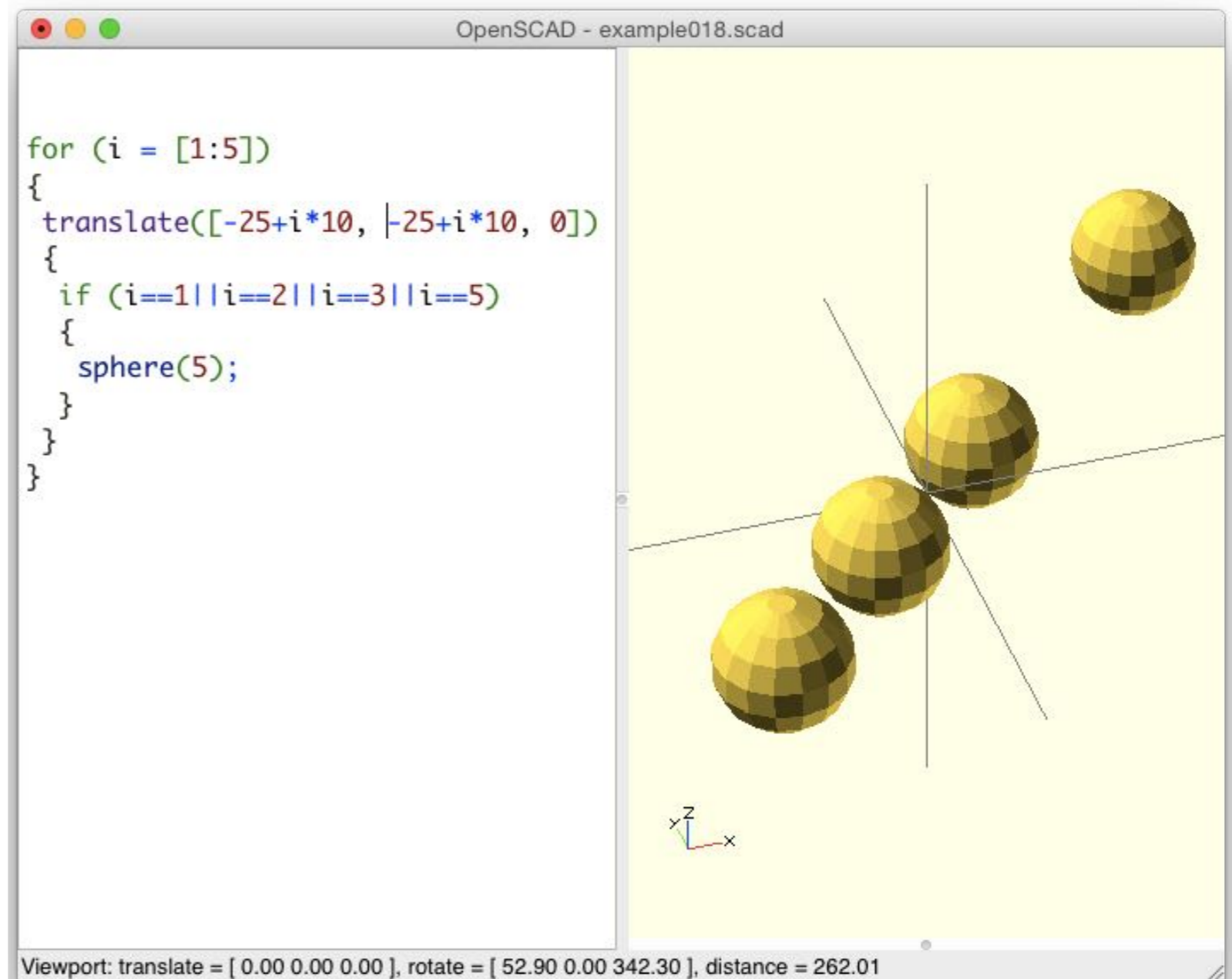
# Boolean operations

- **union ()**
- **difference ()**
- **intersection ()**



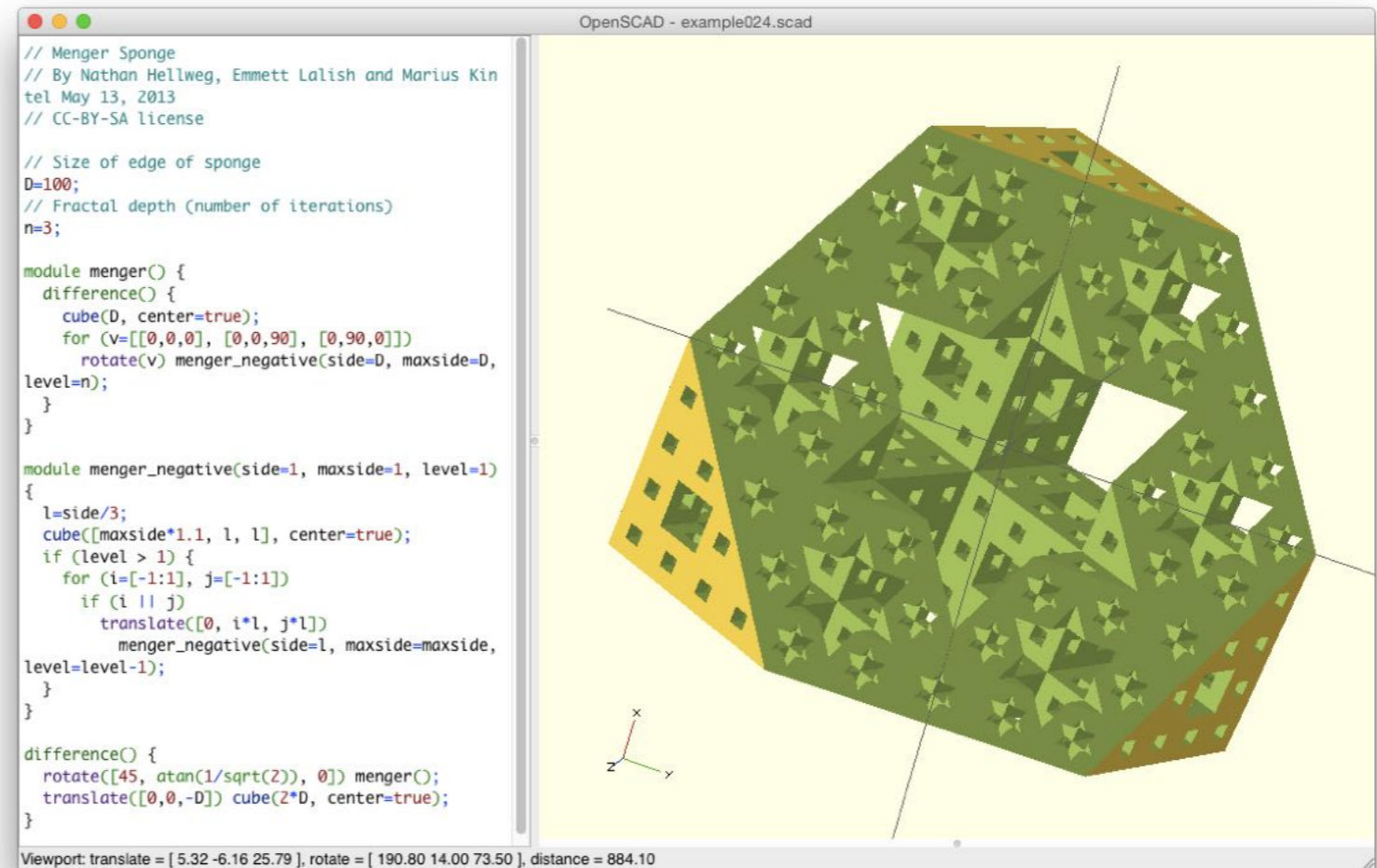
# Loops & conditions

- **for** ( i = [start:end] )  
  { ... }
- **if** ( condition )  
  { ... }
- ... other usual stuff



# Others

- many mathematical functions are available: power, root, trigonometrical, log, exponential, etc...
- functions, modules, include
- 2D primitives, extrusion
- export of 3D models as STL



# List of all commands

## OpenSCAD CheatSheet

### Syntax

```
var = value;  
module name(...) { ... }  
name();  
function name(...) = ...  
name();  
include <...scad>  
use <...scad>
```

### 2D

```
circle(radius)  
square(size,center)  
square([width,height],center)  
polygon([points])  
polygon([points],[paths])
```

### 3D

```
sphere(radius)  
cube(size)  
cube([width,height,depth])  
cylinder(h,r,center)  
cylinder(h,r1,r2,center)  
polyhedron(points, triangles, convexity)
```

### Examples

```
cylinder(10,5,5);  
cylinder(h=10,r=5);
```

### Transformations

```
translate([x,y,z])  
rotate([x,y,z])  
scale([x,y,z])  
mirror([x,y,z])  
multmatrix(m)  
color("colorname")  
color([r, g, b, a])  
hull()  
minkowski()
```

### Boolean operations

```
union()  
difference()  
intersection()
```

### Modifier Characters

```
* disable  
! show only  
# highlight  
% transparent
```

### Mathematical

```
abs  
sign  
acos  
asin  
atan  
atan2  
sin  
cos  
floor  
round  
ceil  
ln  
len  
log  
lookup  
min  
max  
pow  
sqrt  
exp  
rands
```

### Other

```
echo(...)  
str(...)  
for (i = [start:end]) { ... }  
for (i = [start:step:end]) { ... }  
for (i = [...,,...]) { ... }  
intersection_for(i = [start:end]) { ... }  
intersection_for(i = [start:step:end]) { ... }  
intersection_for(i = [...,,...]) { ... }  
if (...) { ... }  
assign (...) { ... }  
search(...)  
import("...stl")  
linear_extrude(height,center,convexity, twist,slices)  
rotate_extrude(convexity)  
surface(file = "...dat",center,convexity)  
projection(cut)  
render(convexity)
```

### Special variables

```
$fa minimum angle  
$fs minimum size  
$fn number of fragments  
$t animation step
```


# 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


**YM YOUMAGINE** Ideas Discover Designers Blog + Add design

### Popular


Show more



**Wimshurst Electrostatic Generator**  
WH16 updated 14.o6.2o14  
♥ 26 J



**Human Brain**  
The human brain - almost full size - remixed from jmil  
♥ 7 RichRap



**Entrepreneurship activity**  
Subject: Start your own business The children wrote a 'business plan' and used their own  
♥ 3 Alant


a MakerBot Industries website

# THINGIVERSE


 THINGS TOOLS BROWSE BLOG

Digital designs for real, physical objects. A Universe of Things!


### Featured Things (3,397 things)




**Clutch**  
Created by [PrettySmallThings](#)  
28 days ago




**Romo Gen 2 Laser Cutting Template and...**  
Created by [romotive](#)  
17 hours ago



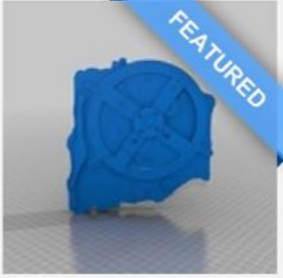
**Micro Dumper**  
Created by [blecheimer](#)  
3 days ago




**Hollow impossible heart**  
Created by [mowi](#)  
3 days ago




**PaperFly**  
Created by [clothbot](#)  
2 days ago




**Antikythera Mechanism**  
Created by [CosmoWenman](#)  
5 days ago




**Mithran Star Strider**  
Created by [dutchmogul](#)  
4 days ago



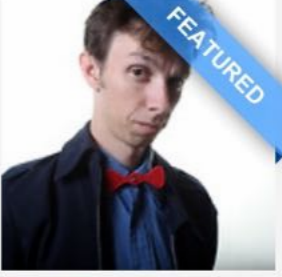
**working Air Engine**  
Created by [JDCUBED](#)  
5 days ago



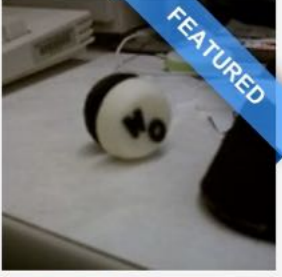
**Head of a horse of Selene**  
Created by [CosmoWenman](#)  
5 days ago



**Portrait of Alexander the Great**  
Created by [CosmoWenman](#)  
5 days ago



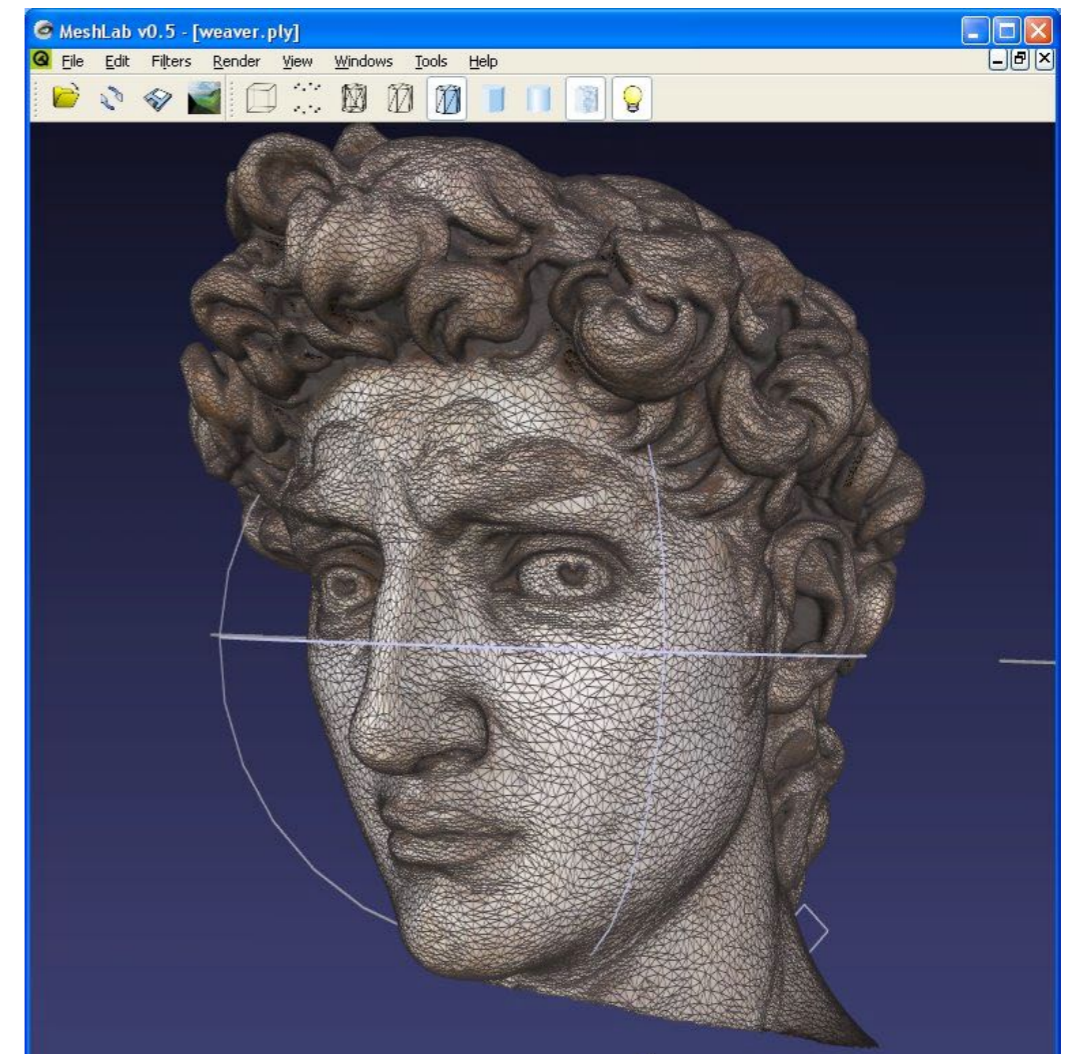
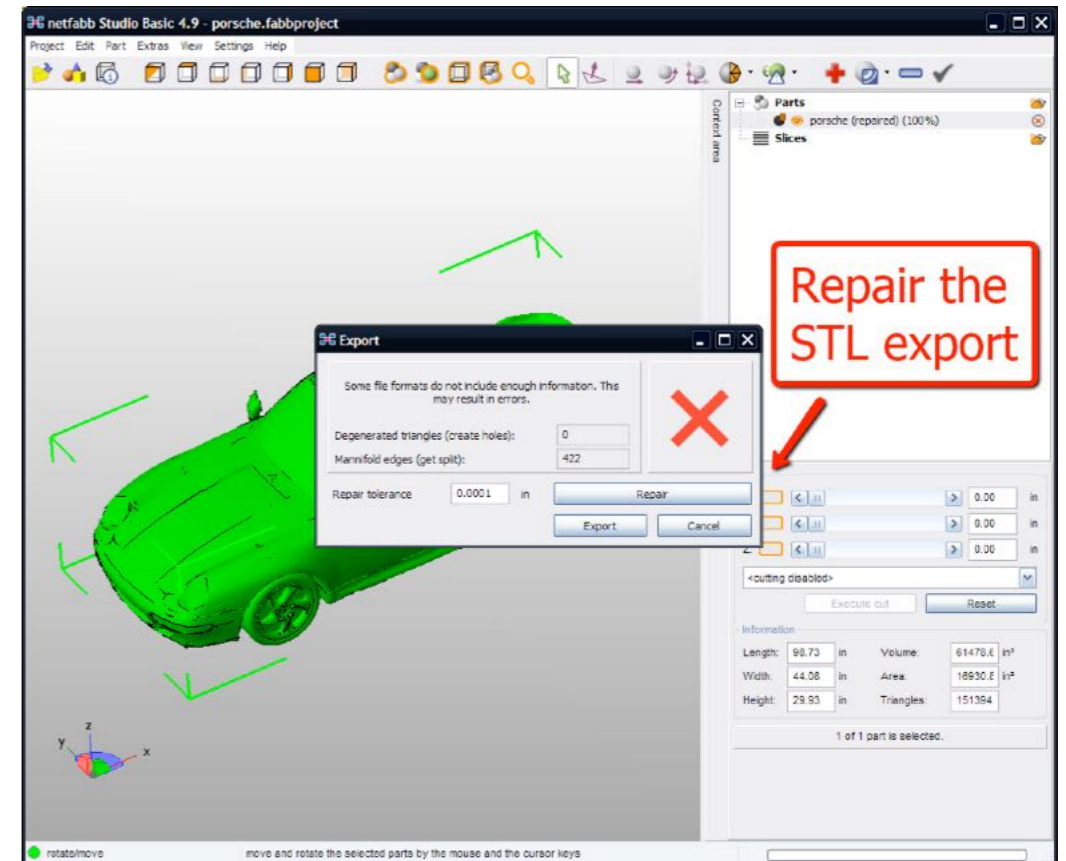
**Bow Tie**  
Created by [ElectricSlim](#)  
10 days ago



**WO - YO (YO YO)**  
Created by [theroar](#)  
11 days ago

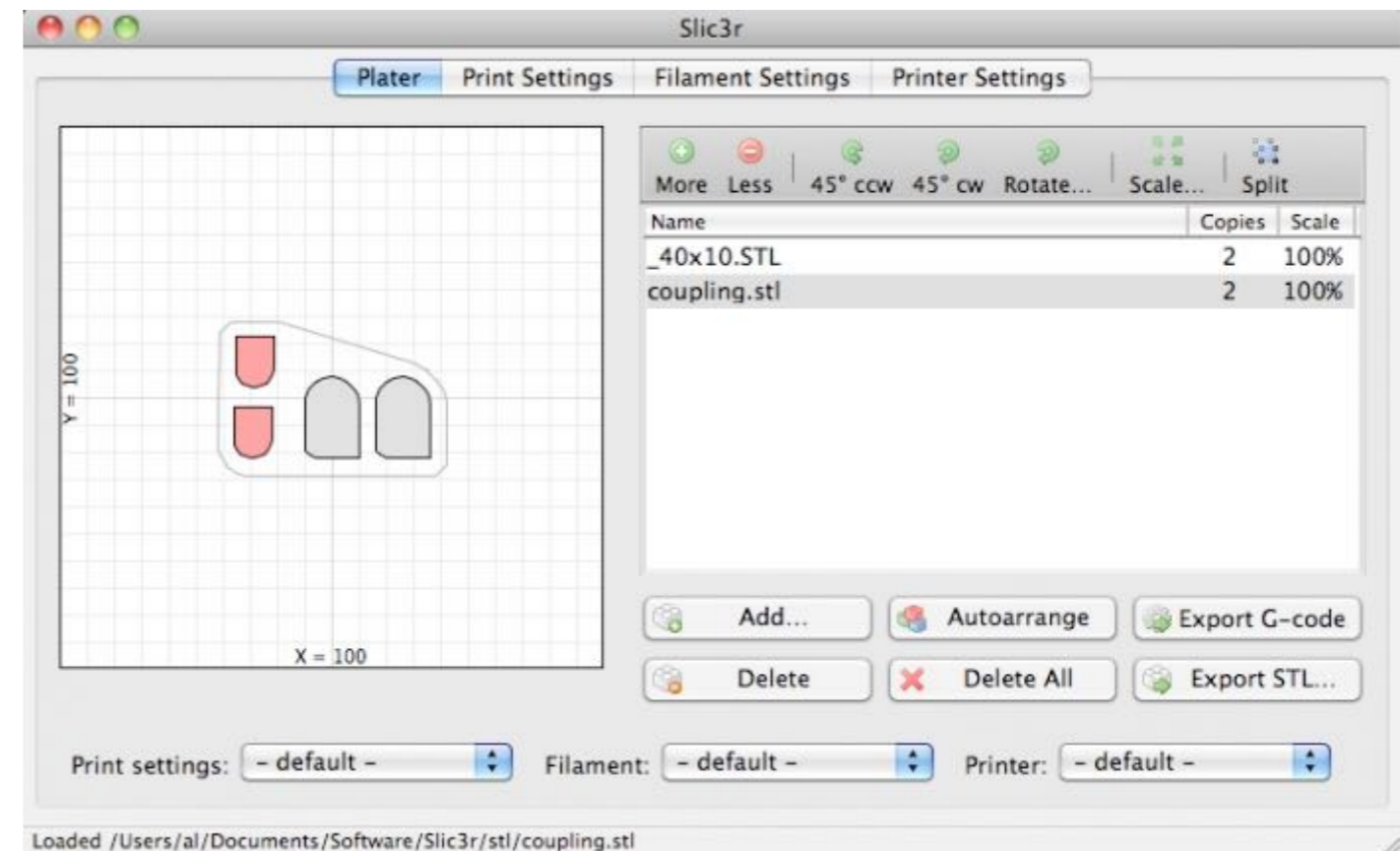
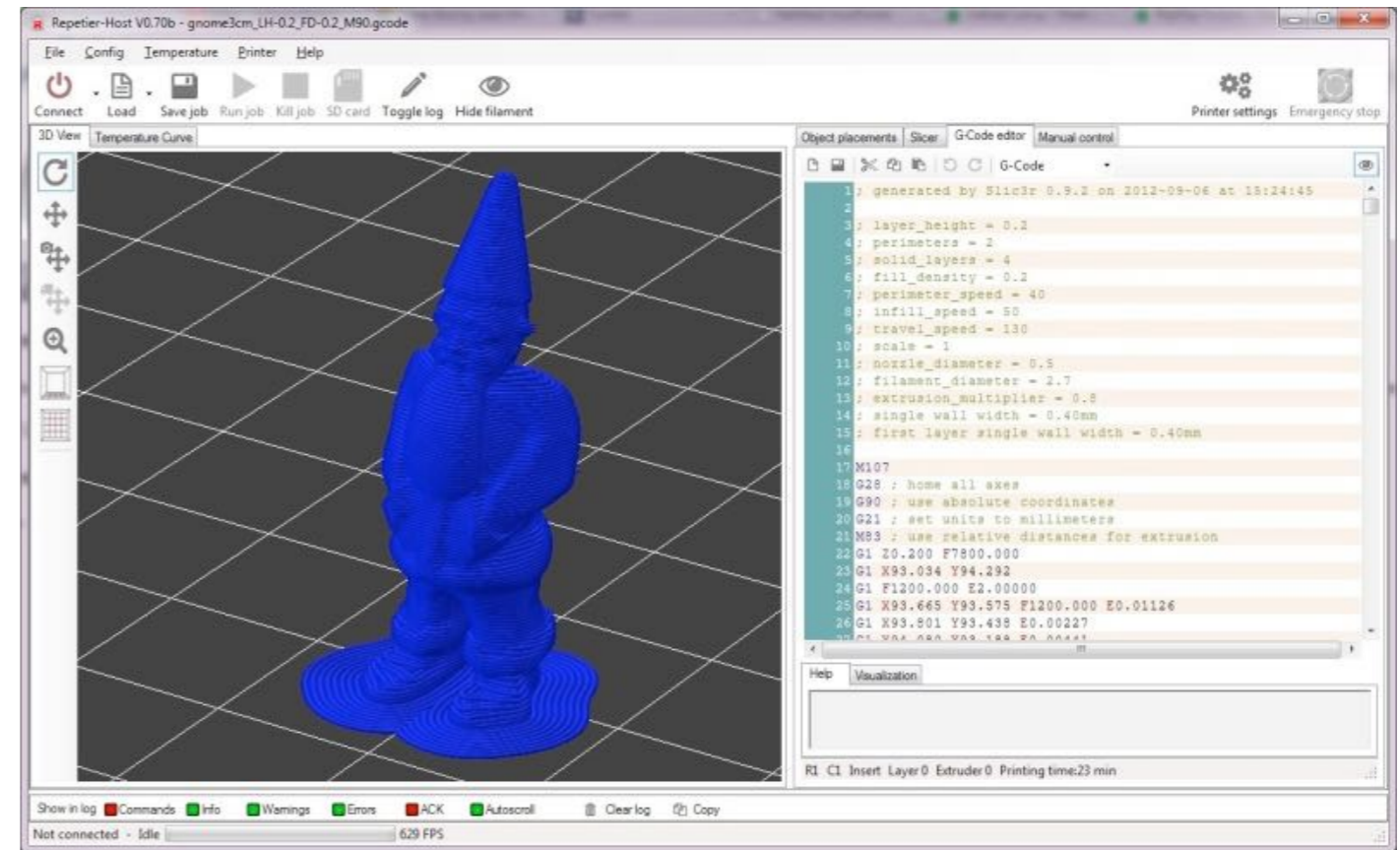
# #2 - Check & repair

- 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)
  - **Meshmixer** from Autodesk (great for STL mashups)
  - also Cura and Slic3r can repair meshes in their latest version



# #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*.

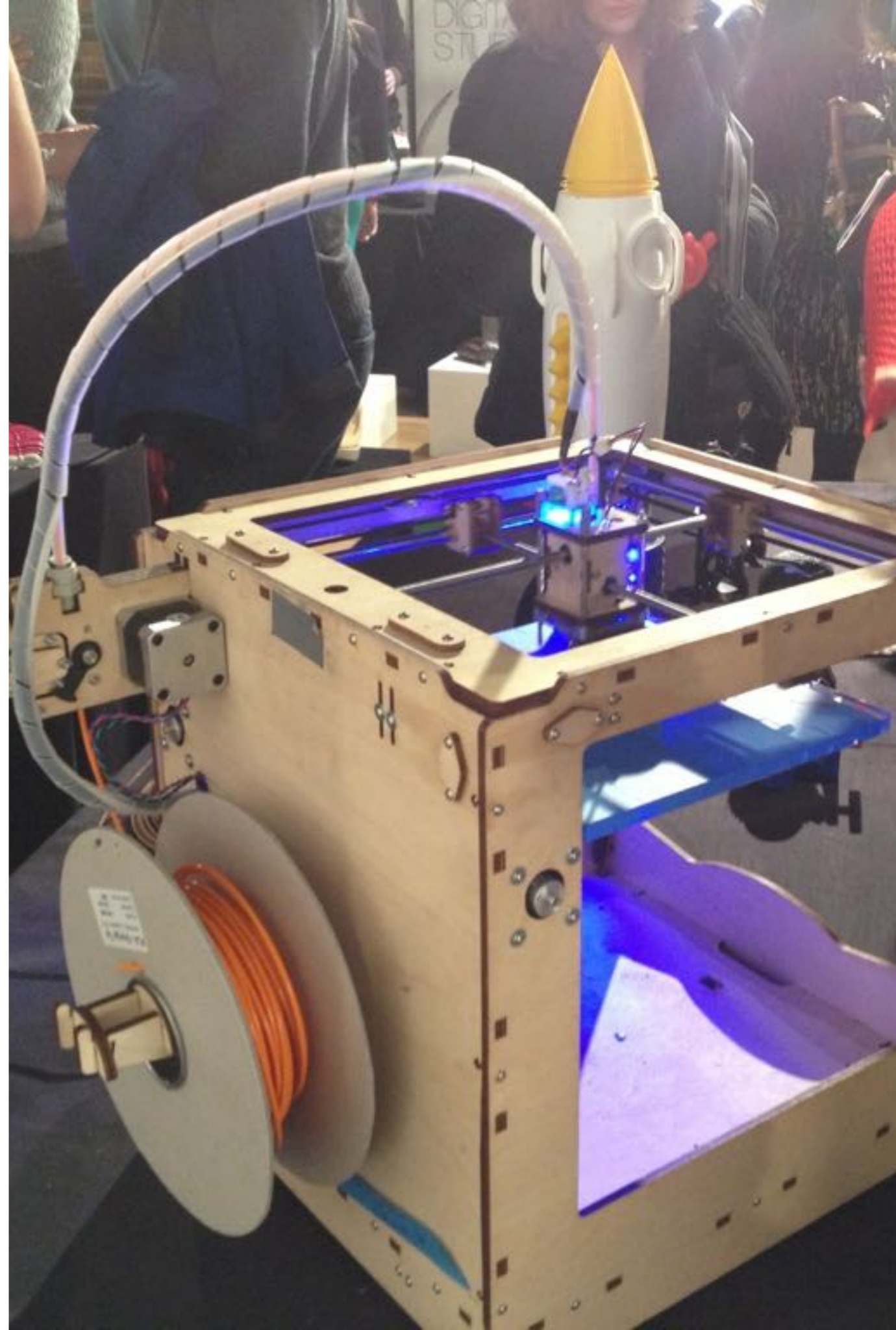




## #4 - Prepare the printer

---

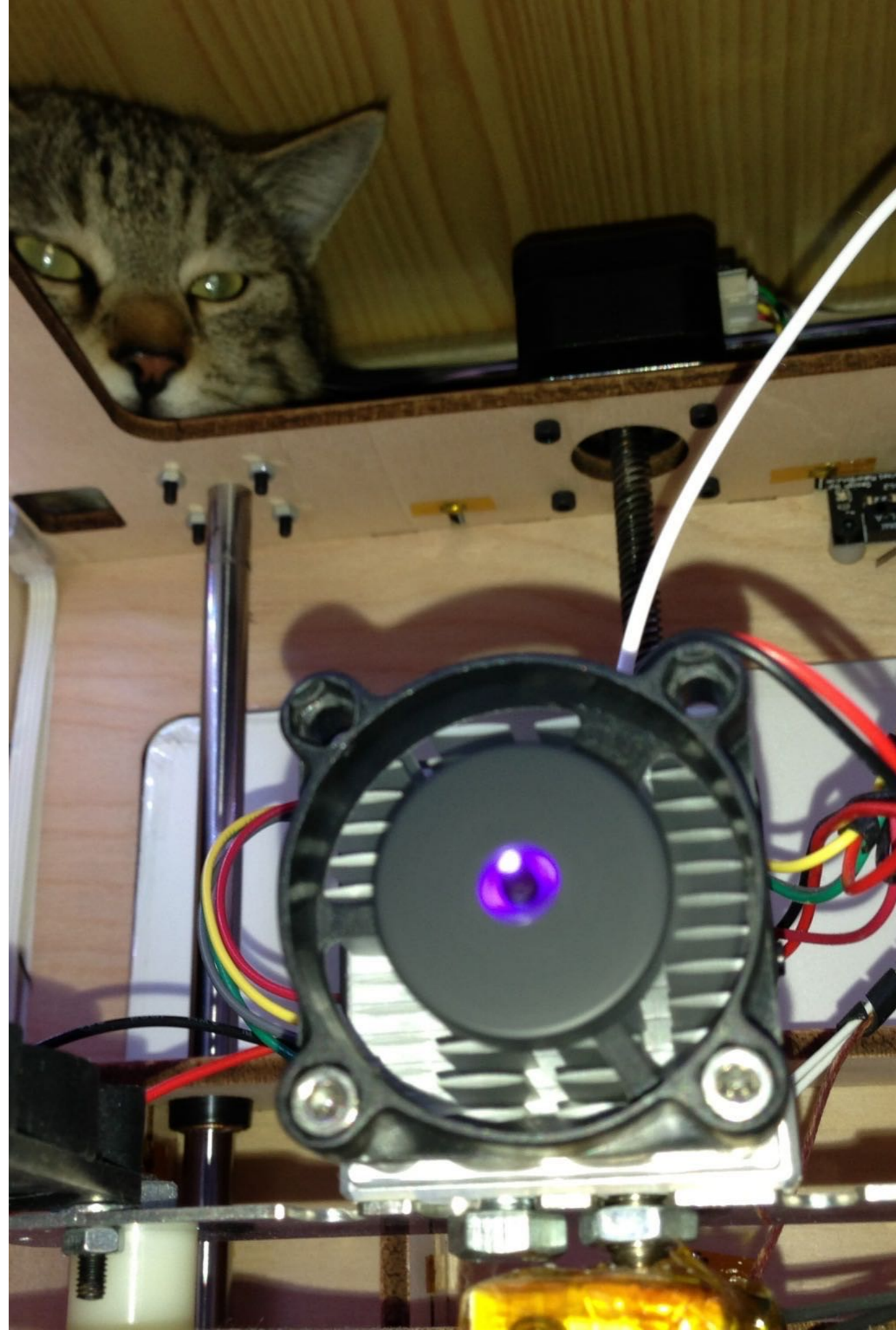
- calibrate (level) the platform (printing bed) and clean it
- pre-heat the printing head
- load the plastic filament into the extruder
- extrude some plastic, in order to fill the nozzle
- start the print ;-)



## #5 - Wait until finished

---

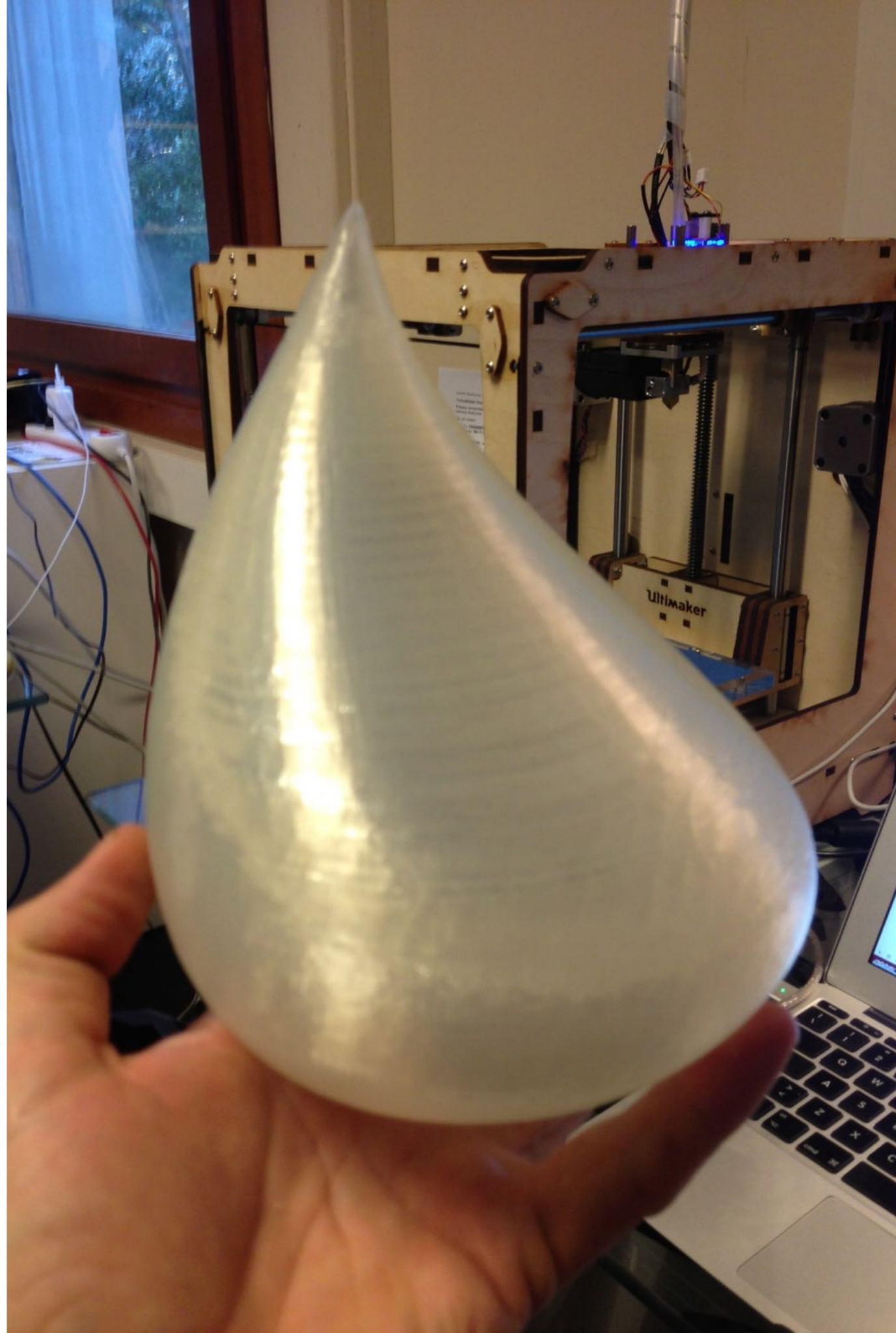
- Printing time for a small object can be 10-20 minutes.
- For an object the size of an apple, can be up to 1 hour and more (it depends on resolution, infill, and printer speed).
- Bigger objects can take 10+ hours, complex ones even 20+ hours...
- May be dangerous to leave a 3D printer unattended when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



## #6 - Finishing

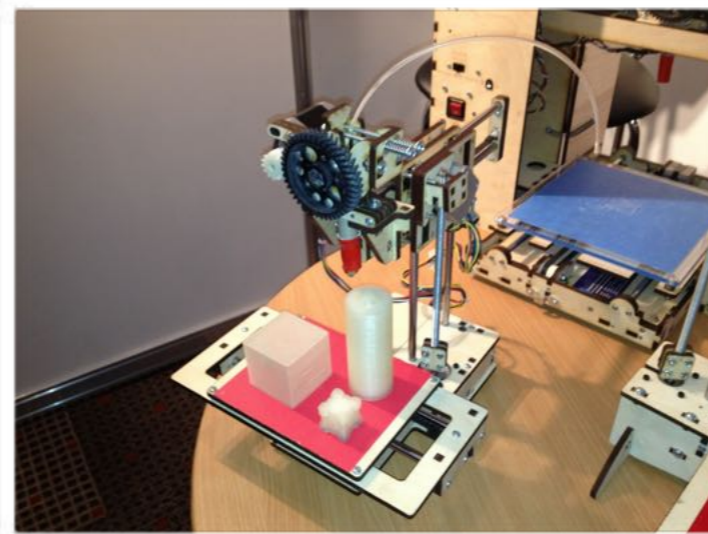
---

- 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.



# 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).
- Final object size may be incorrect because of thermal contraction/dilation, always check (measure and and compensate)





Combining multiple prints can be a solution...

**World's First  
3D Printed**



**Kayak**



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

---

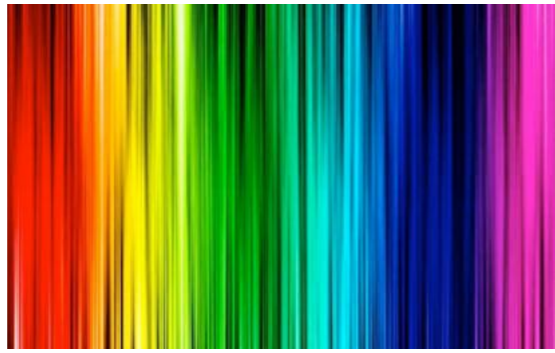
- **ABS** (Acrylonitrile Butadiene Styrene), petroleum based plastic (used for the Lego™ bricks)
- **PLA** (Polylactic Acid or Polylactide), a *biodegradable* plastic made out of plant starch
- **Nylon** (®Taulman 618/645 or “grass cutter” filament –available at lower cost)
- **PVA** (Polyvinyl Alcohol), *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.

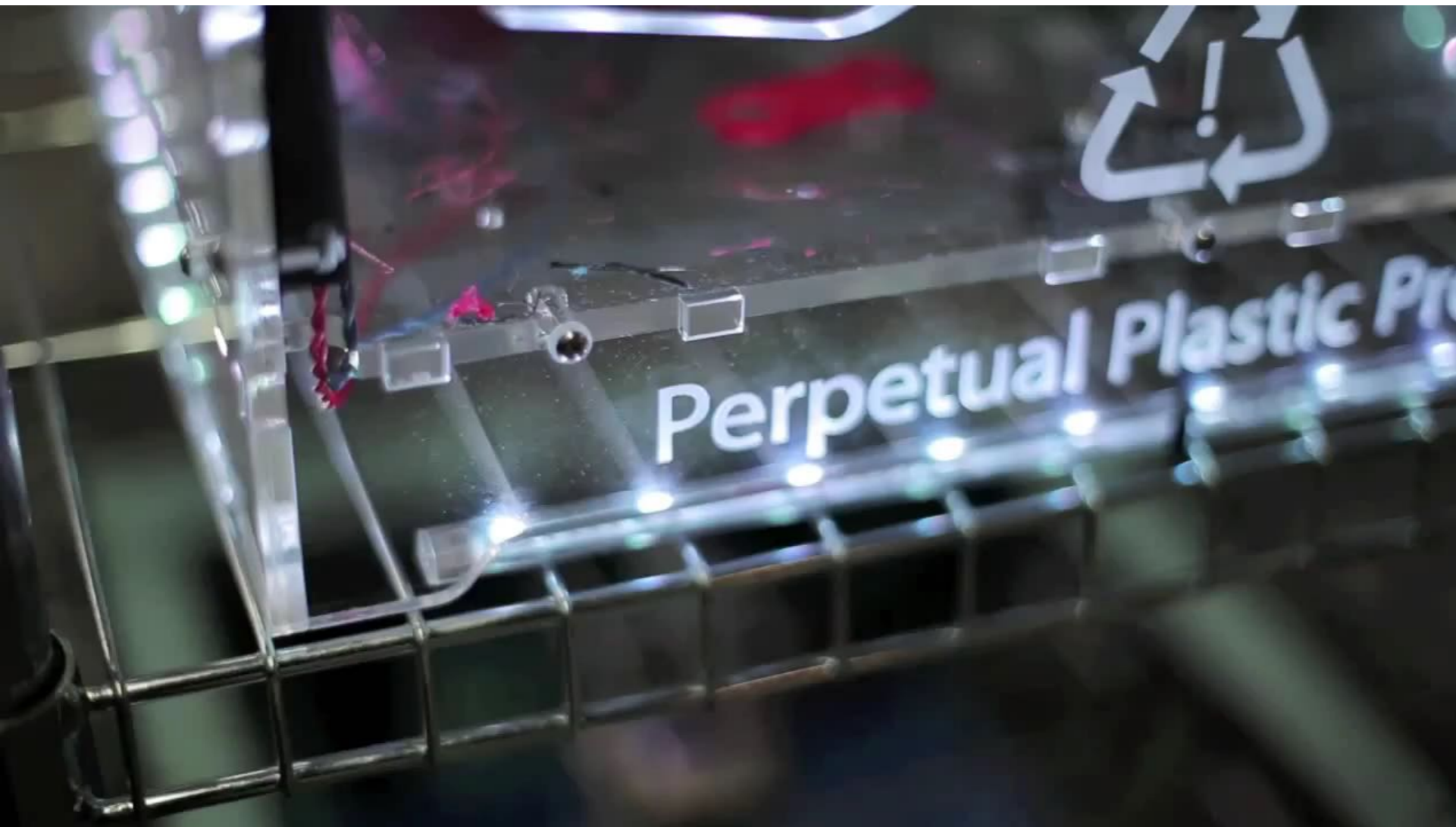


# Recycling plastic

---

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

- make 3D-printed objects from recycled plastic



# 3DP as Service

makexyz Find 3D Printers Find all makers Sign In List your services - free!

## Find a 3D printer near you.

Find 3D Printers

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

3D HUBS PRINTING ABOUT LOG IN 3D PRINT

7 Print Hubs in Trieste

3D print in Trieste

### Want to make a 3D Print?

3D Hubs connects you to a worldwide community of 3D printers and makers, ready to help you get started on your next project. Fast, affordable and local 3D printing.

#### Wanted: Mayor

Learn more

28 Makers

7 Print Hubs

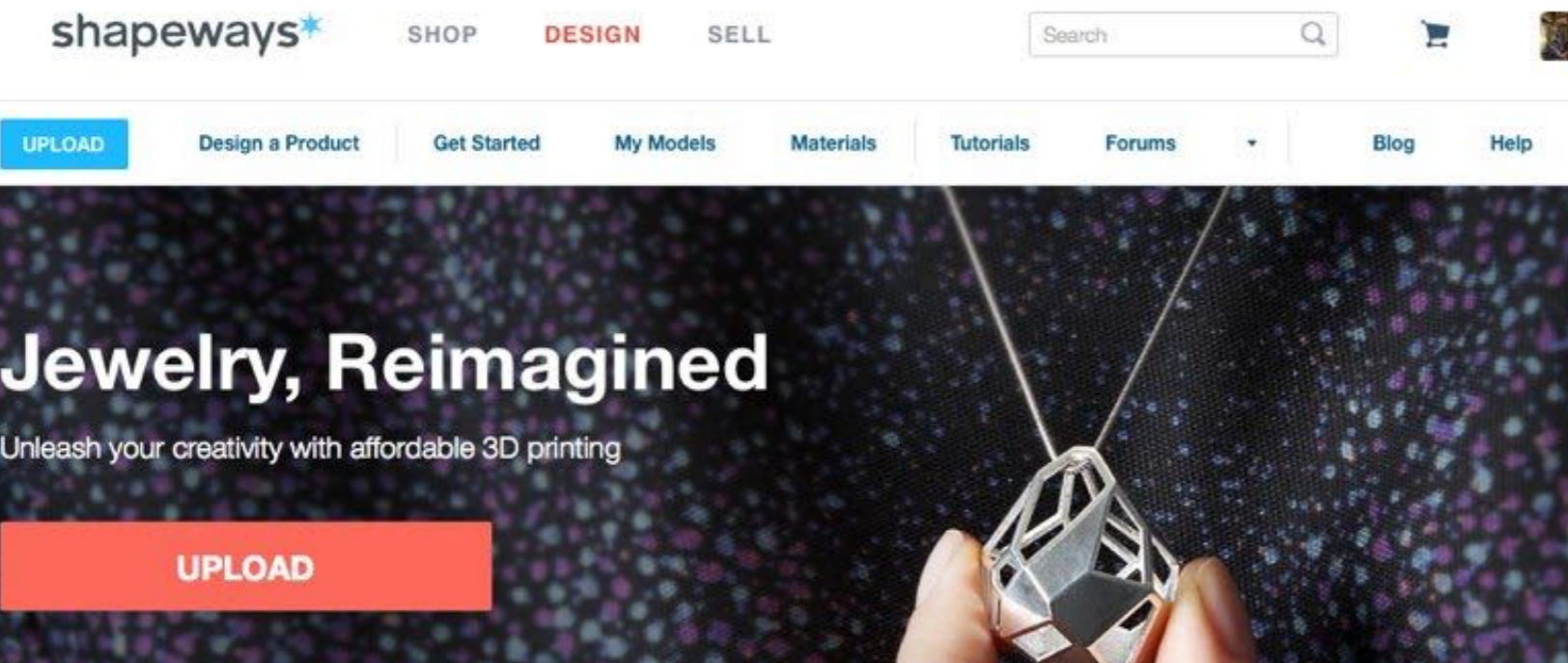
INVITE FRIENDS

[www.3dhubs.com](http://www.3dhubs.com)

# 3DP as Service



[www.3ditaly.it](http://www.3ditaly.it)



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

# The Periodic Table of Materials



Display material icons



high detail resin



paintable resin

Rank

**Symbol**

material



stainless steel



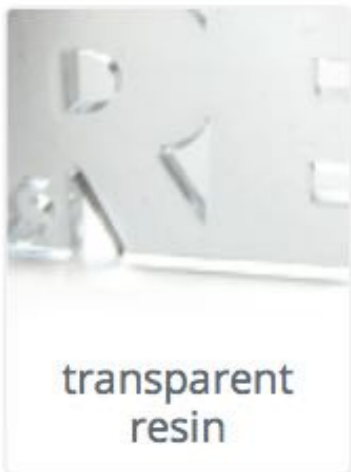
polyamide



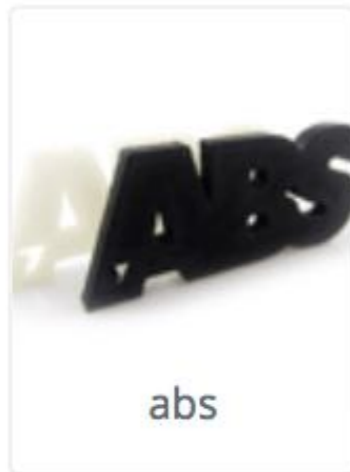
alumide



multicolor



transparent resin



abs



titanium



gold



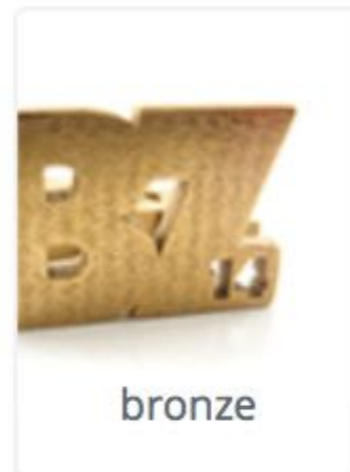
silver



prime gray



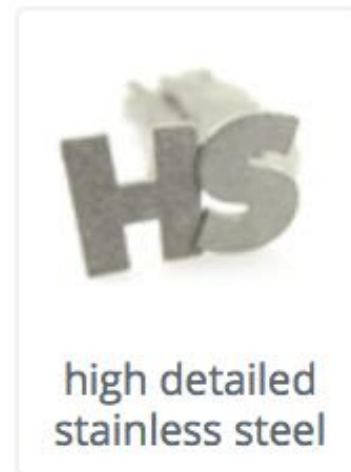
brass



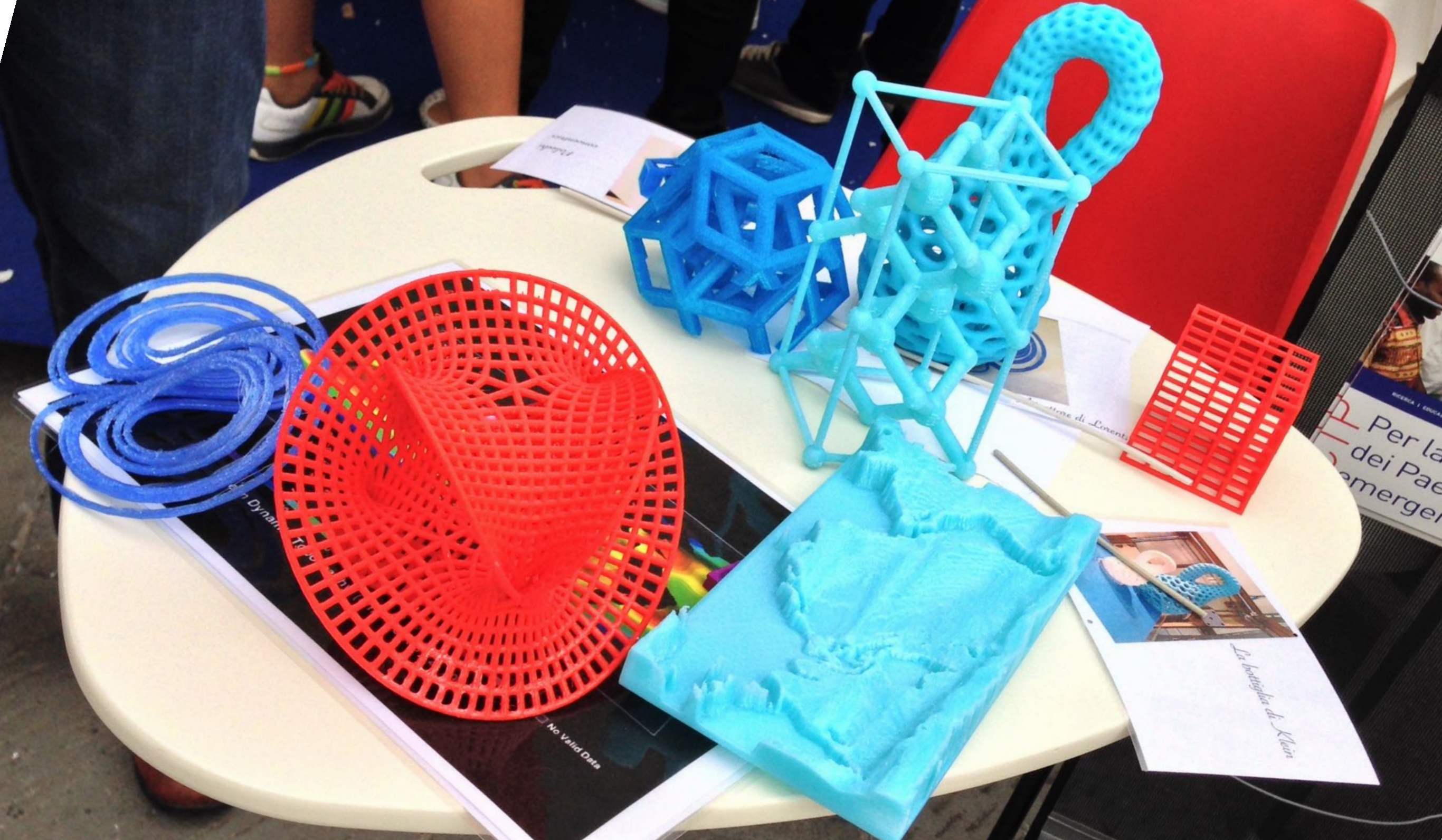
bronze



ceramics



high detailed stainless steel



3DP: what is it for?

... still looking for an answer!

3DP for....

everyday life!



3DP for....

Art!



**Testa del cavallo di Selene**  
Acropoli, Atene, 438-432 BC  
Fregio est del Partenone, presso il British  
museum di Londra





Cosmo Wenman

KNMER 406  
*Paranthropus boisei*  
Age: 1.7 million years  
Element: Cranium  
Locality: Ileret, East Turkana, Kenya  
Date of Discovery: 1969

# Cloning objects

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

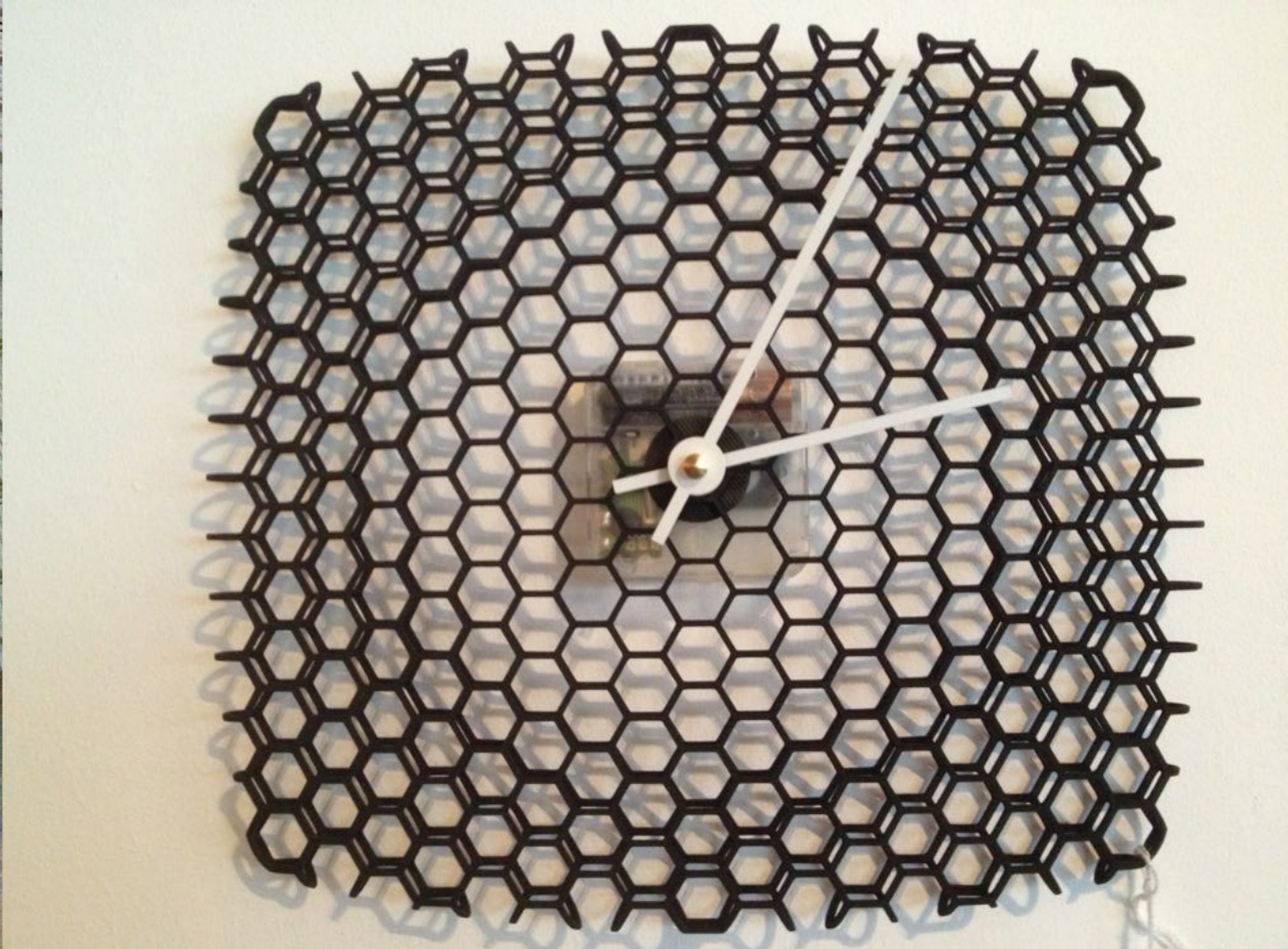


A model (left) was digitally acquired by using a  **3D scanner**, the scanned data processed using **MeshLab**, and the resulting **3D model** used by a **rapid prototyping** machine to create a resin replica (right)



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.

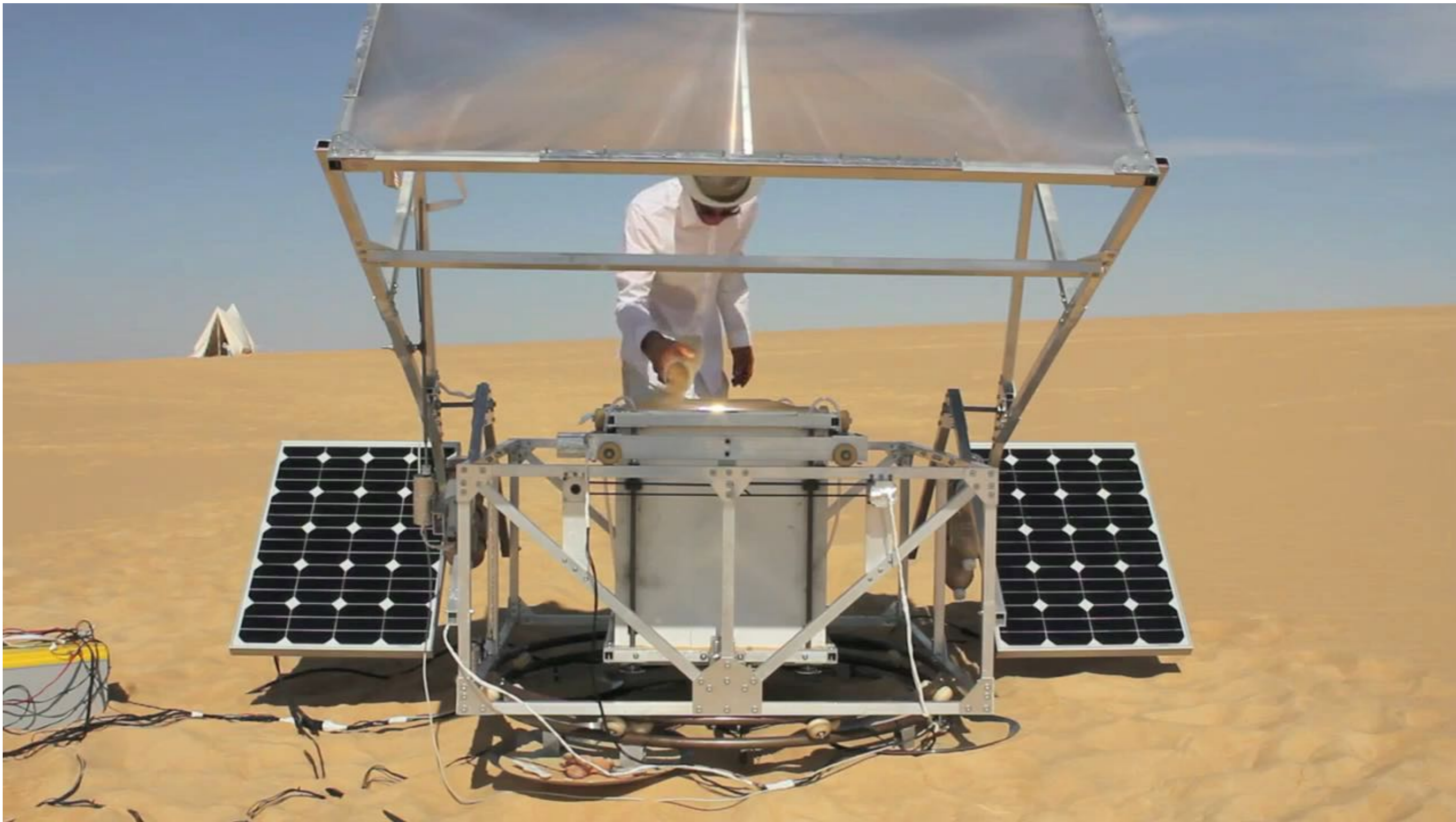
***Met3D***



3Dizingof.com

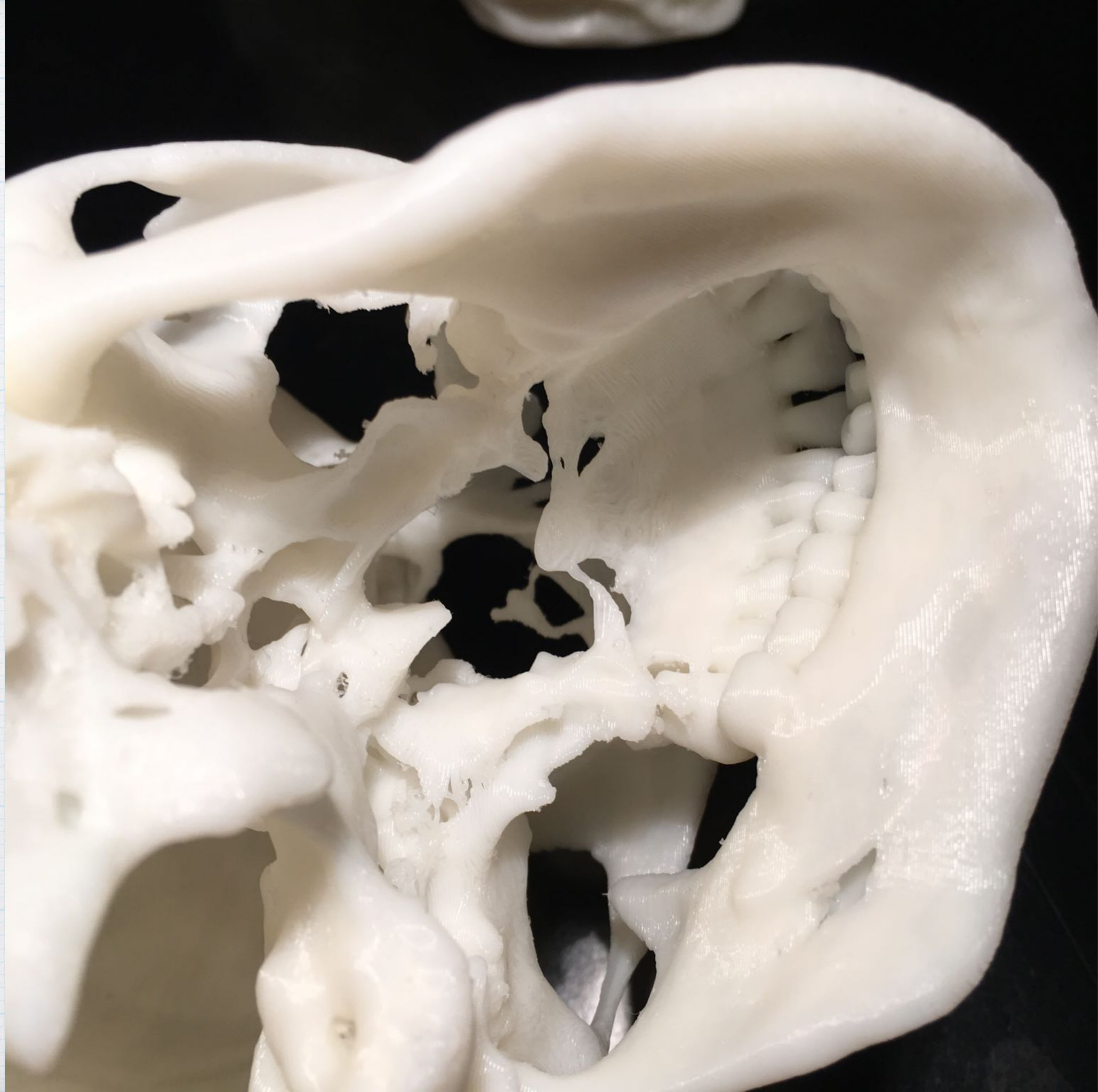


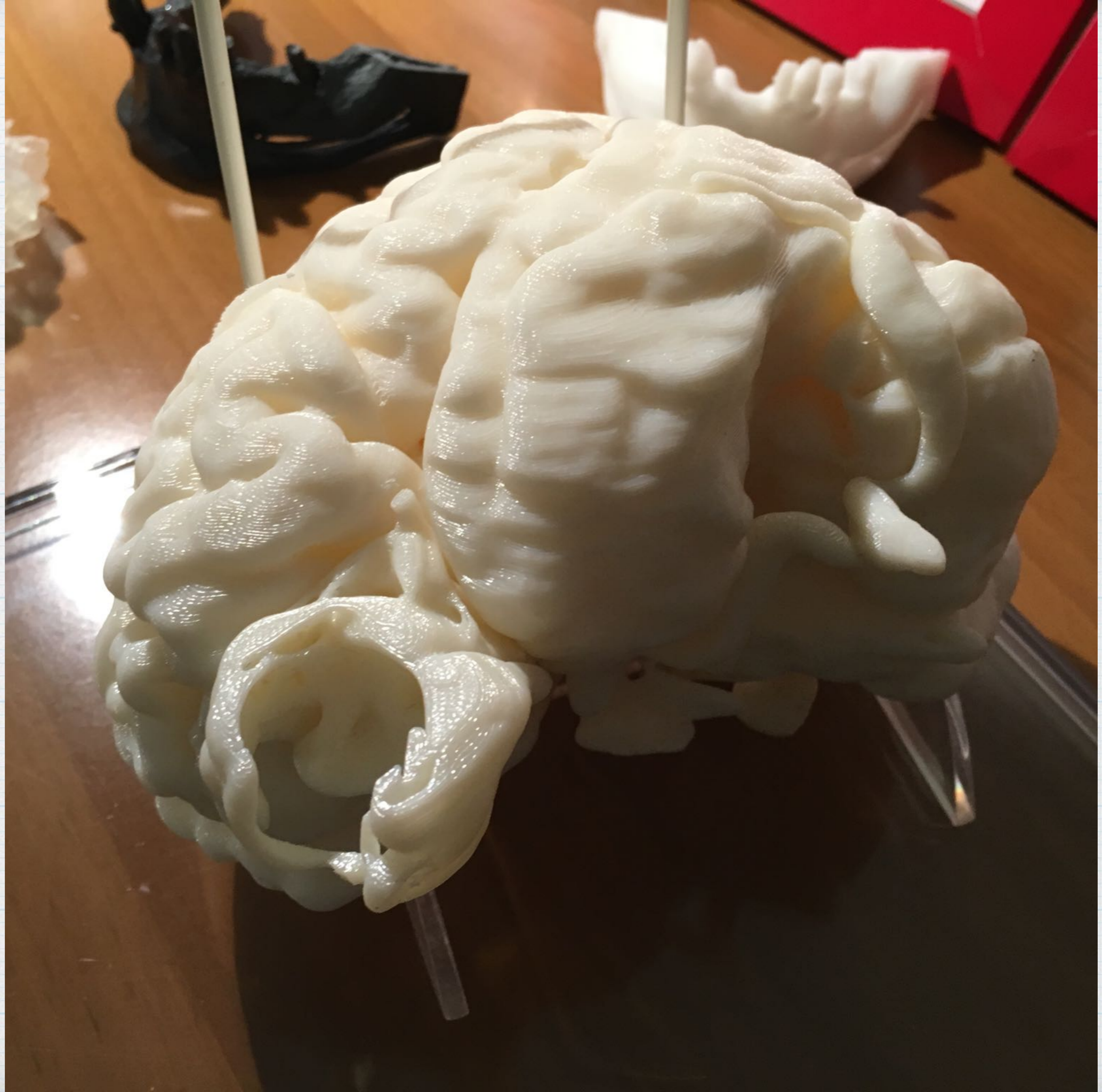
nervous system



Markus Kayser







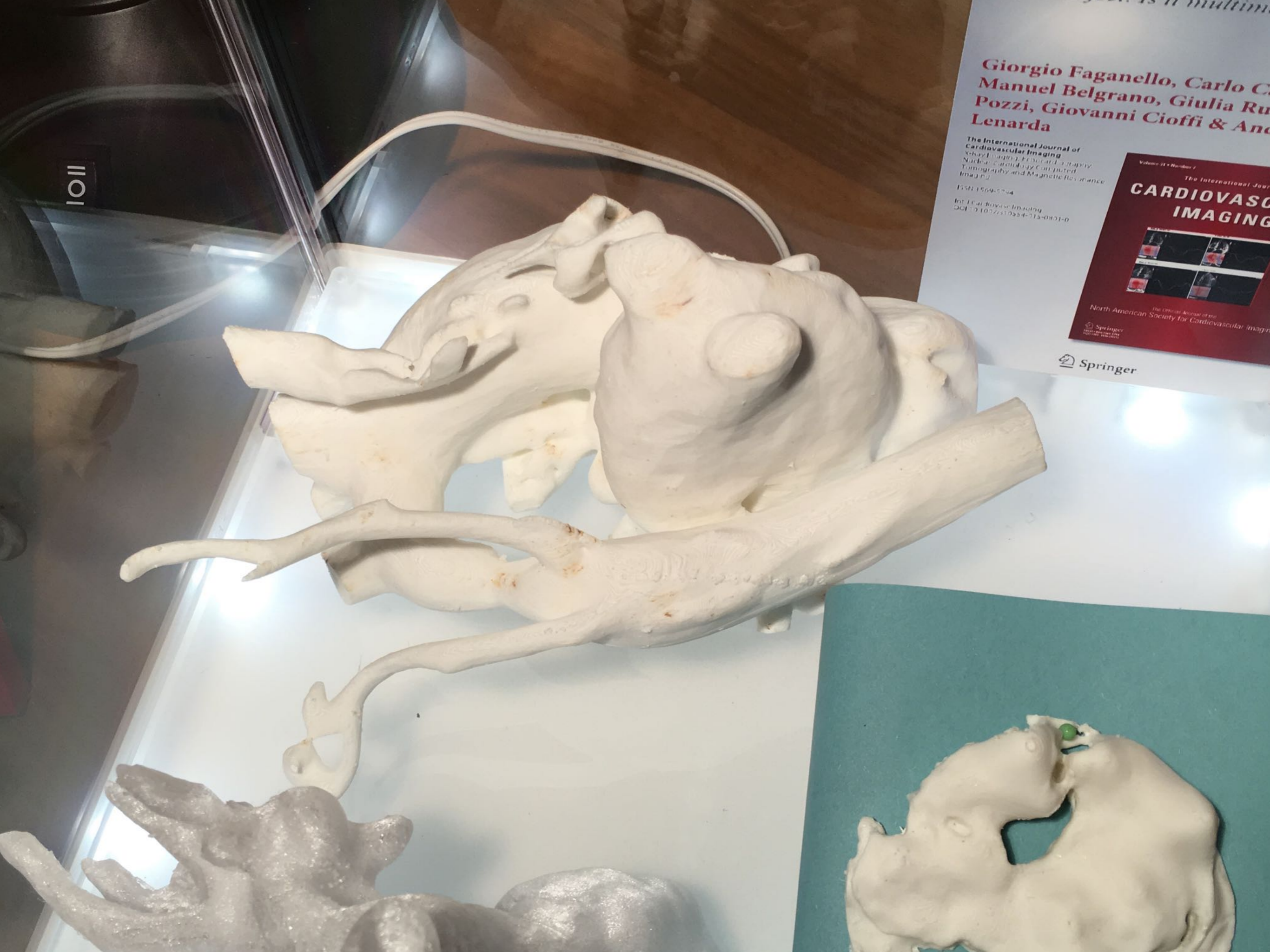


# Coartazione Aortica COA

Lo scopo del modello 3D è quello di migliorare la didattica tra  
Cardiologo e specialista Medico o tra Cardiologo e paziente se  
finalizzato all'ottenimento del consenso informato, con una  
diagnostica integrata che mira al Well Care

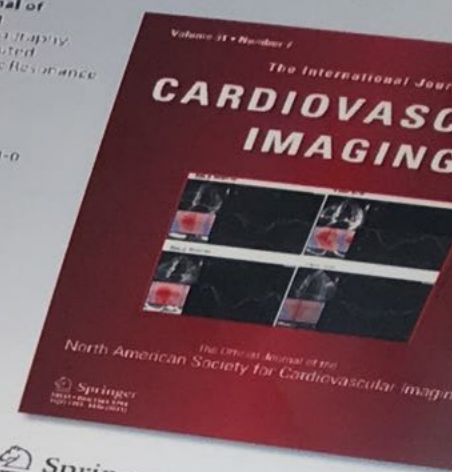
**3D Printer Surgery di Campana**  
[info@3dprintersurgery.com](mailto:info@3dprintersurgery.com) - +39 3479441717



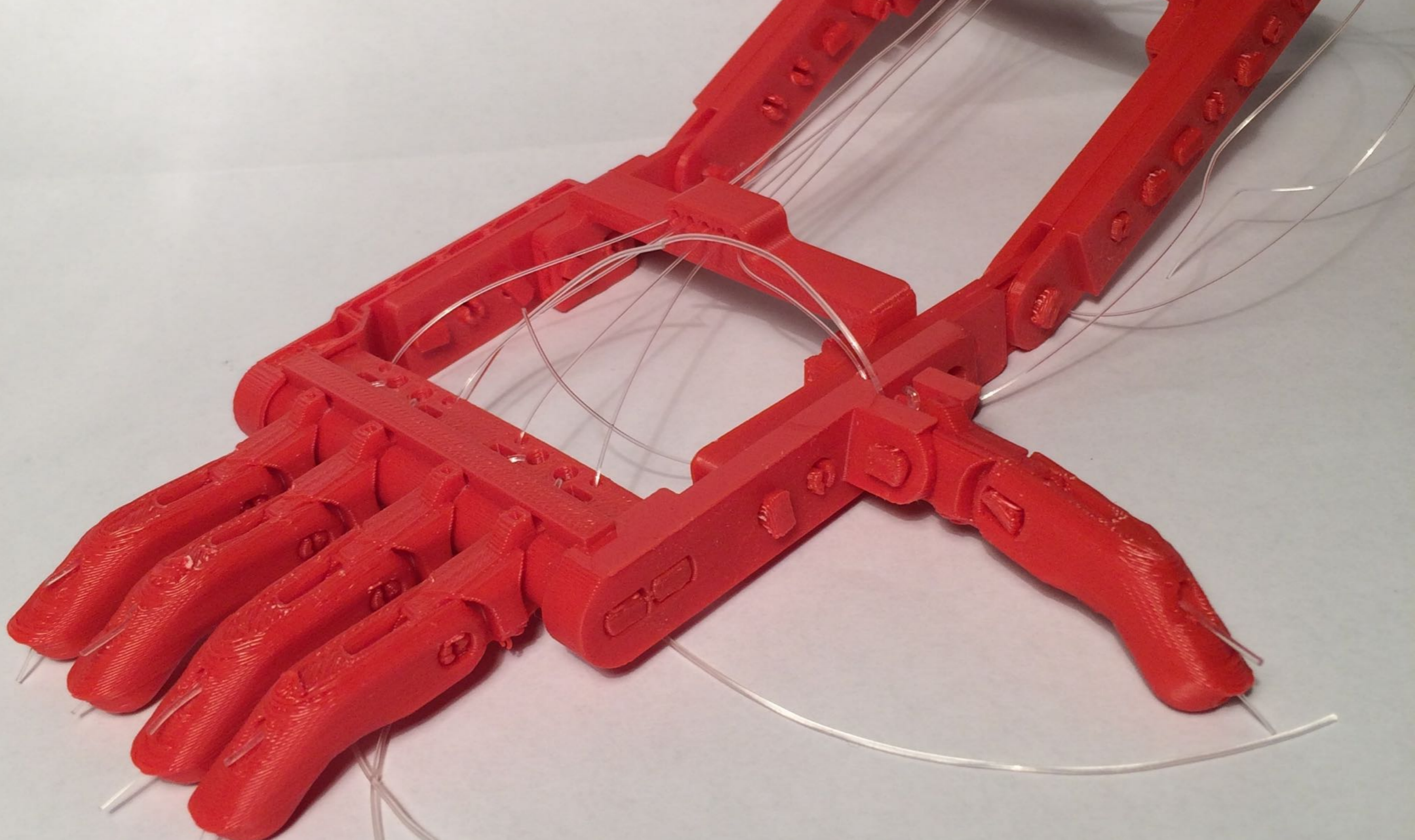


Giorgio Faganello, Carlo C...  
Manuel Belgrano, Giulia Ru...  
Pozzi, Giovanni Cioffi & An...  
Lenarda

The International Journal of  
Cardiovascular Imaging  
X-ray Imaging, Echocardiography,  
Nuclear Cardiology, Computed  
Tomography and Magnetic Resonance  
Imaging  
ISSN 1569-5794  
Int J Cardiovasc Imaging  
DOI 10.1007/s10554-015-0801-0



Springer



Possible applications for  
physical disabilities

... maybe the most ethical use!

Right angle, 90 degree, assistive device (spoon) for someone with, for example, limited grip strength or control. Quick design and prototype of assistive device. This demonstrates that anyone with beginner skills and freeware 3D design software can prototype assistive devices in real time. This project took 20 minutes from design (trueSpace) to printing (Up!3D) in ABS.



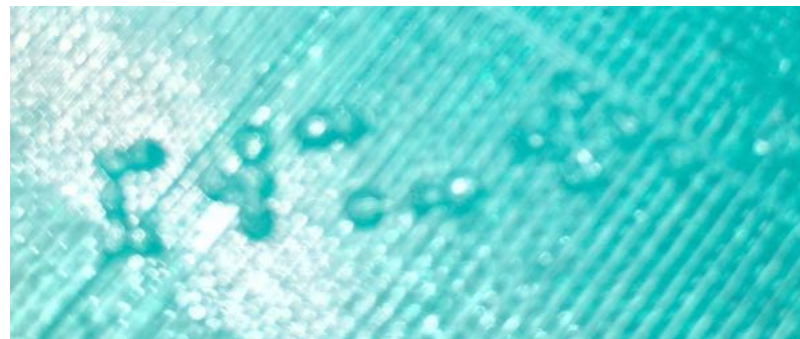
Right angle spoon

<http://www.thingiverse.com/thing:23729>

The planets of our solar system mounted on 3mm thick boards.

All the planets are represented in correct size. The size reference is the sun (1 meter in diameter, could be represented by for example a beach ball )

The planet name is printed in Braille above the planet and the order from the sun is printed below the planet.

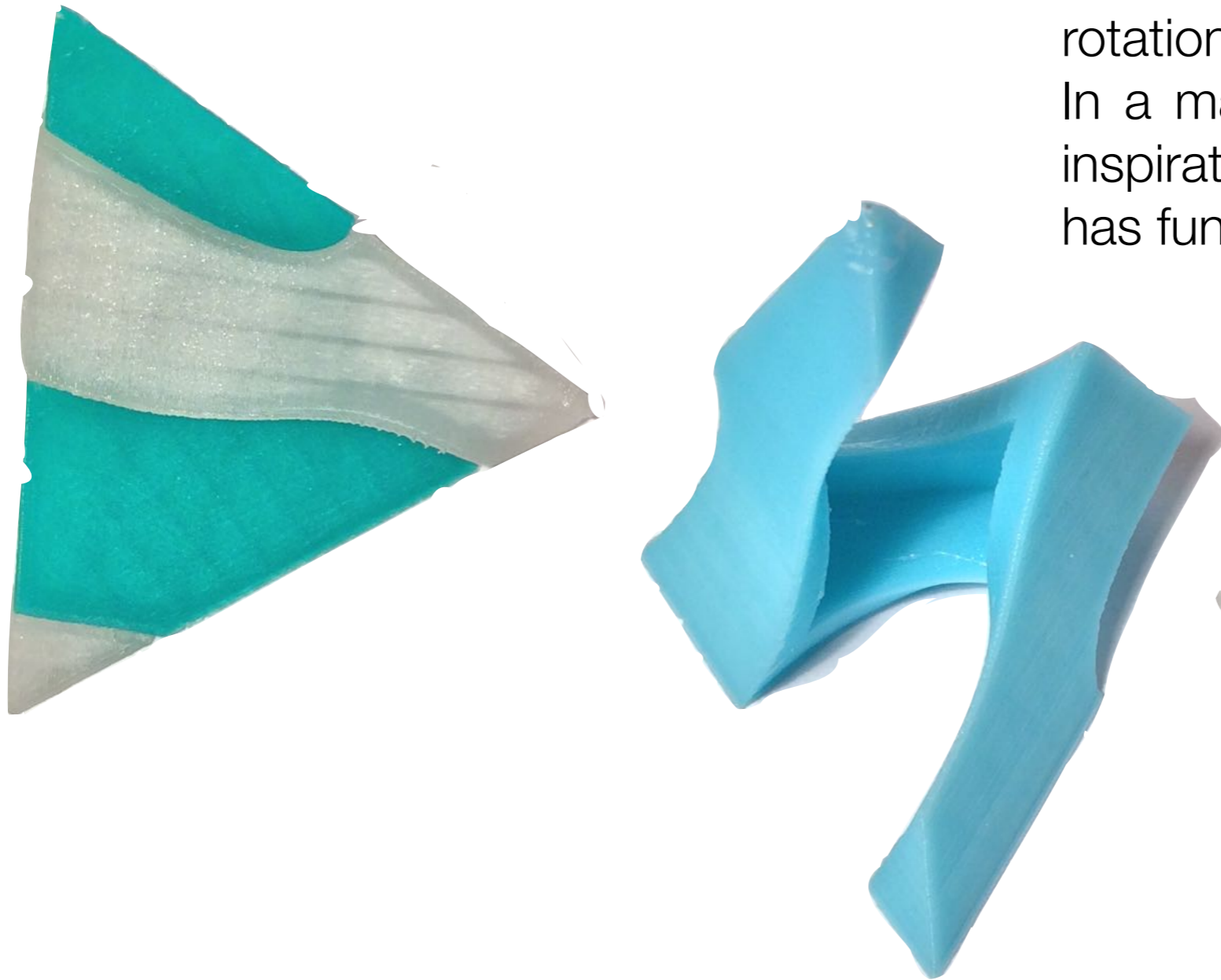


Our solar system for the blind

<http://www.thingiverse.com/thing:65916>

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>

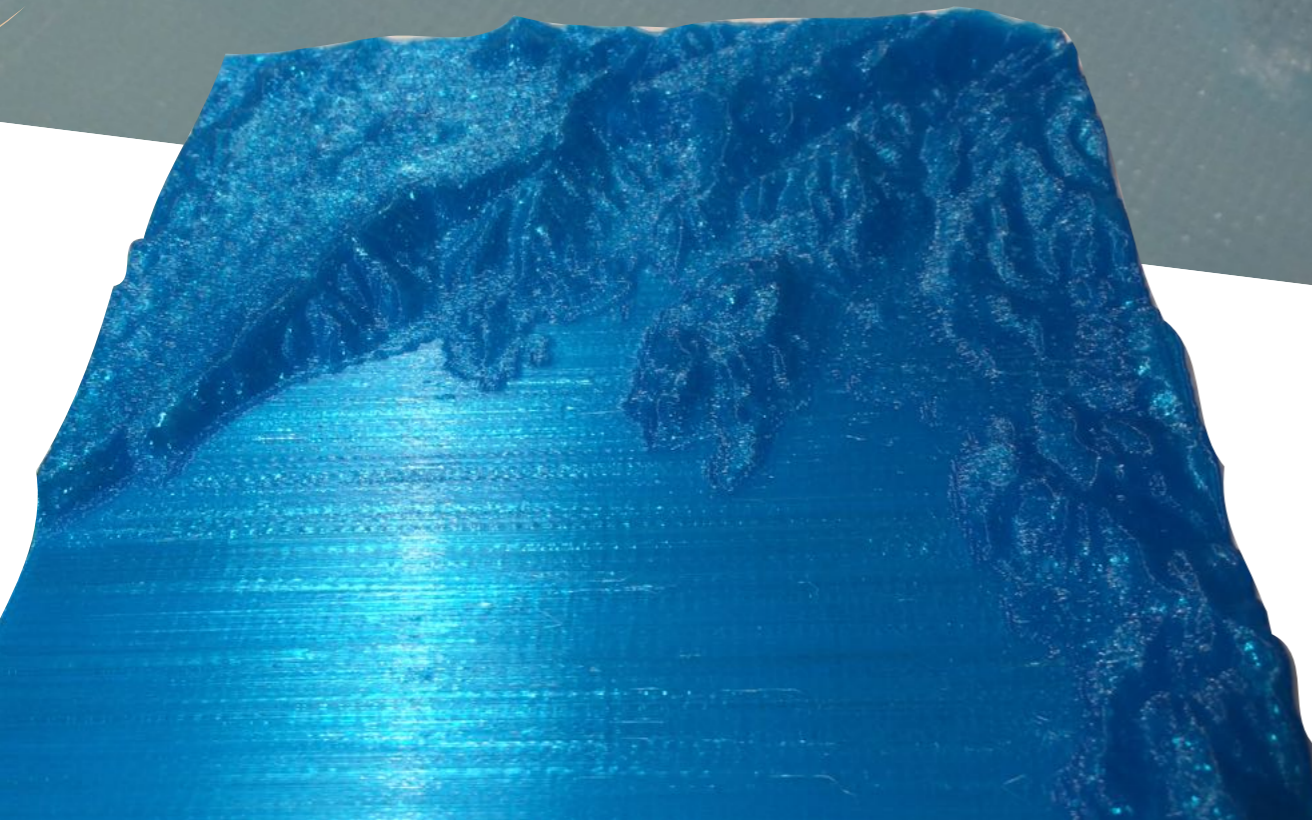
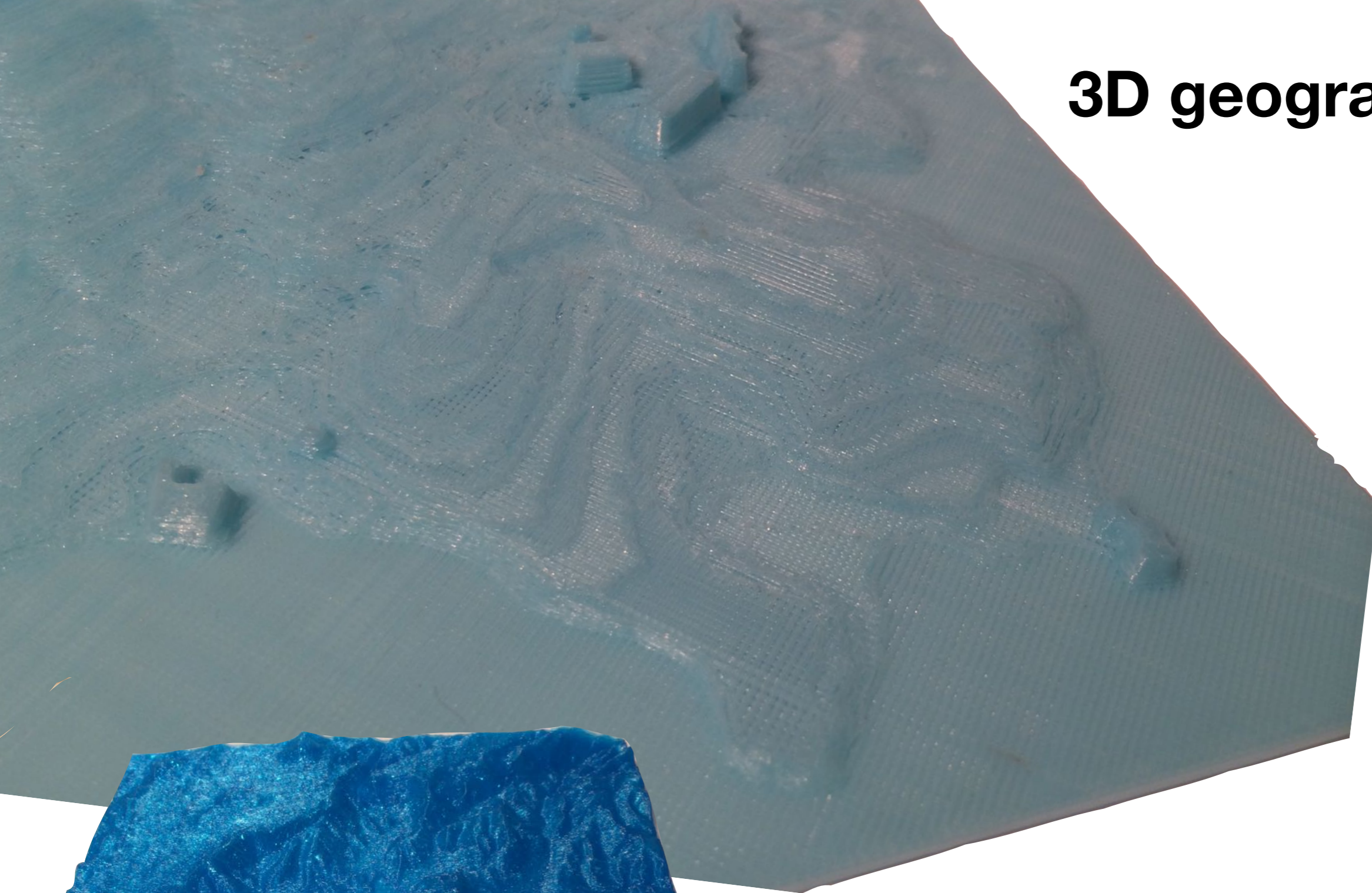


Double Helix of DNA

<http://www.thingiverse.com/thing:10398>

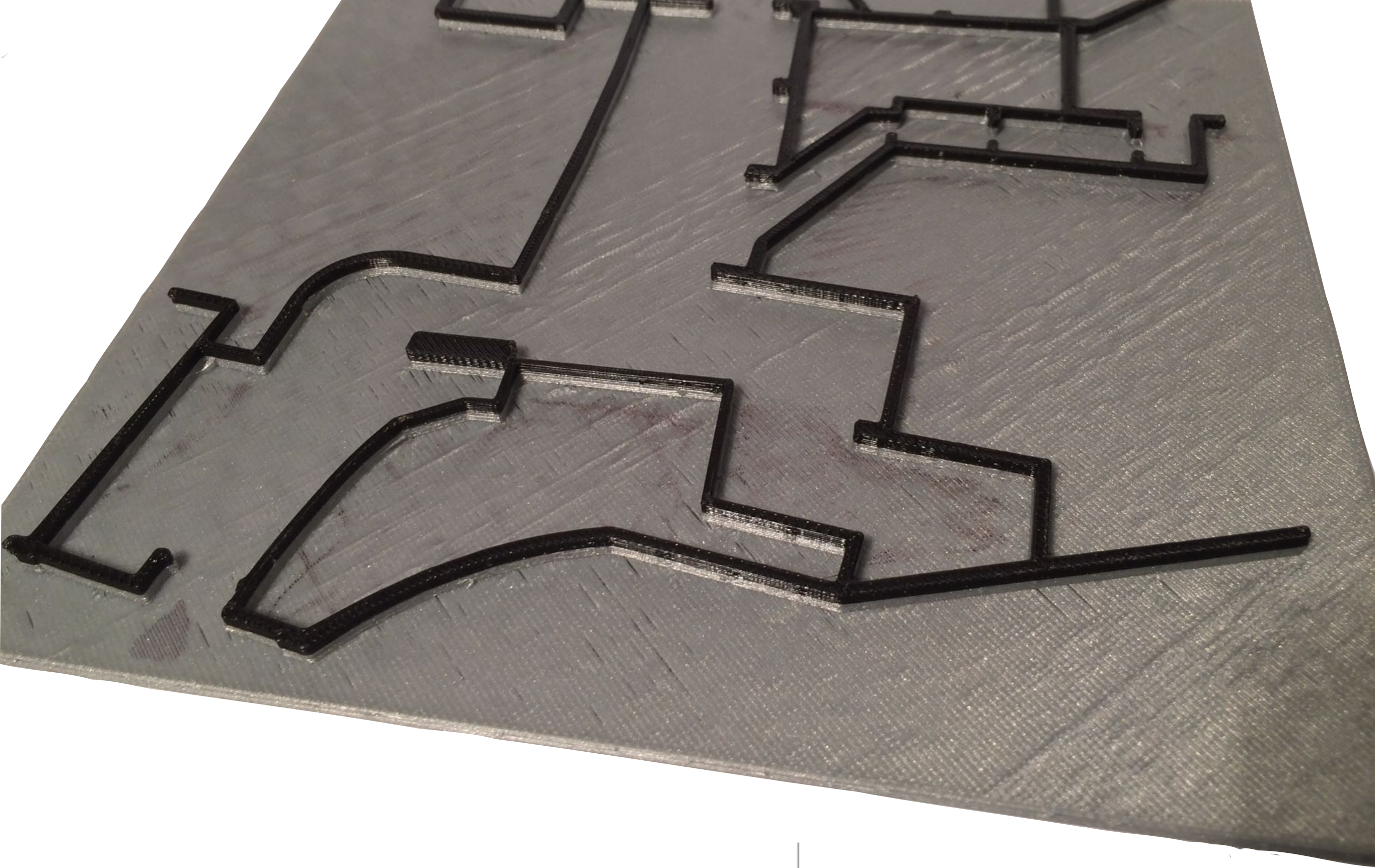
<http://www.thingiverse.com/thing:17343>

# 3D geographical maps



ICTP Miramare Campus  
Gulf of Triest  
(by Gaya Fior, [www.32b.it](http://www.32b.it) )





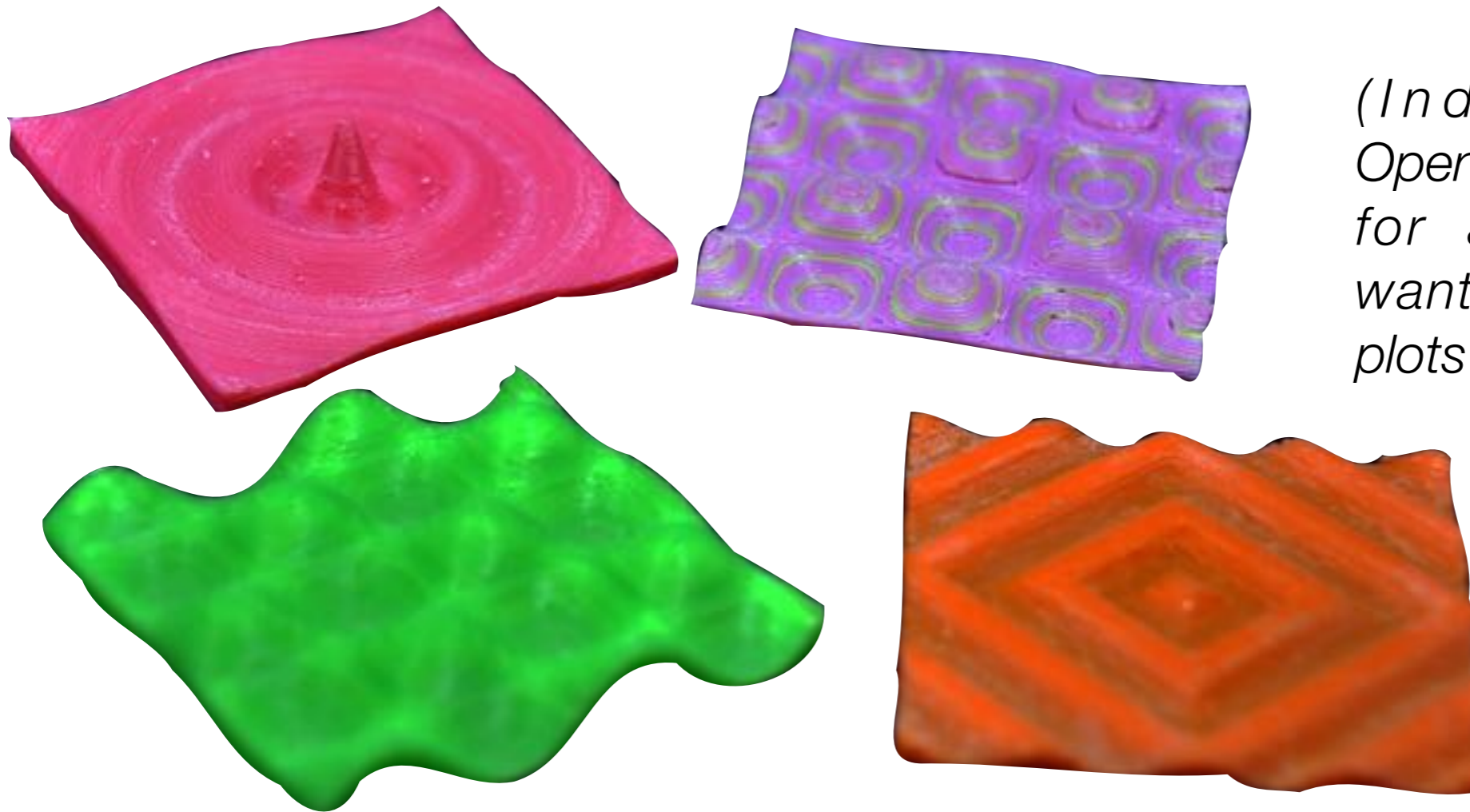
Tactile map of a building

Immaginario Scientifico  
(by C. Fonda, F. Deganis)

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

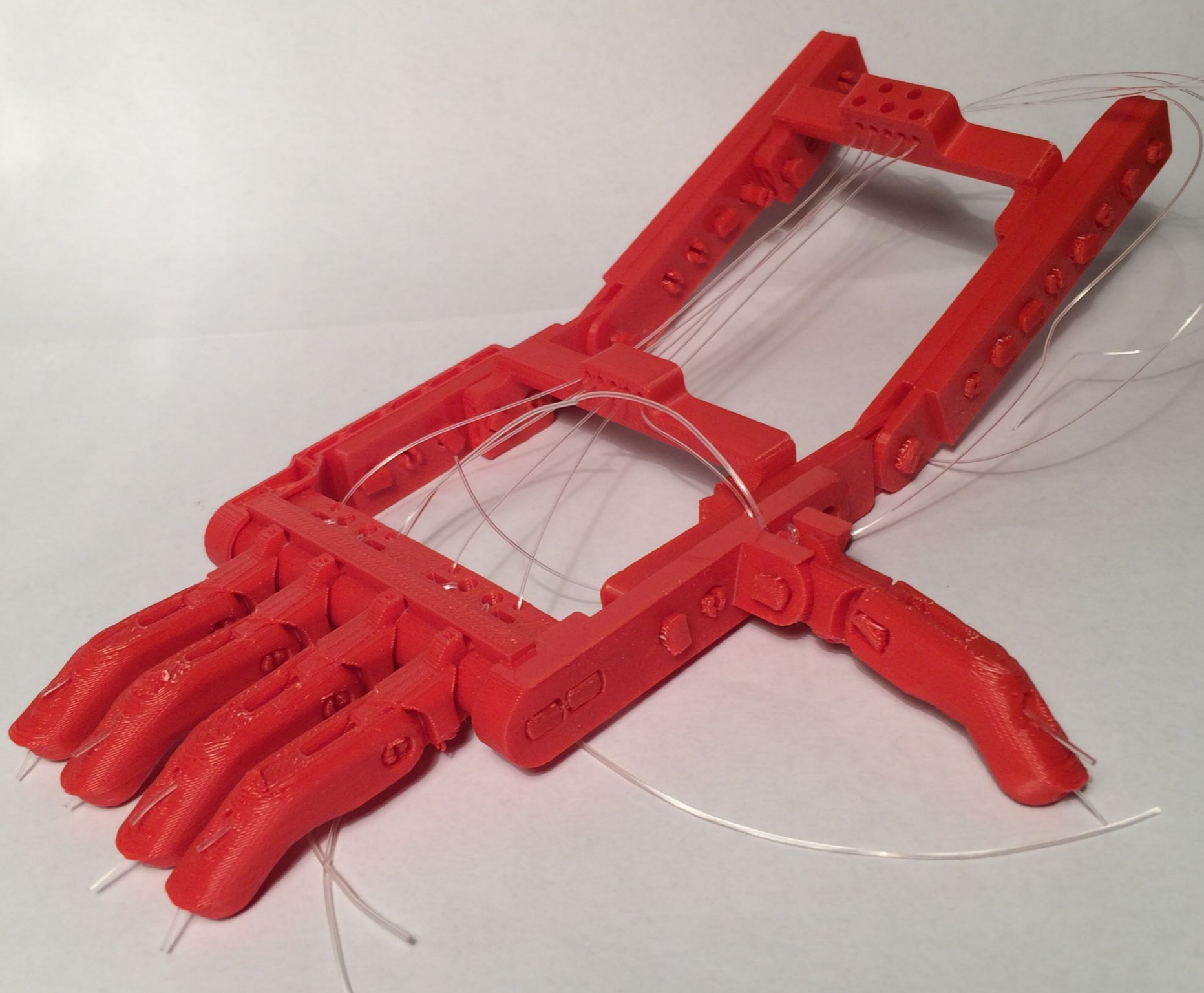
*Yes, you can 3D print 3D surface plots and hold them in your own hands!*

*(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>



Not everyone is fortunate enough to have two hands. Robohand is an open source tool created to help restore the superpowers of humans who are missing the fingers from their hand. The original version was created by Richard Van As and Ivan Owen.

## Robohand

Complete set of mechanical anatomically driven fingers

<http://www.thingiverse.com/thing:44150>

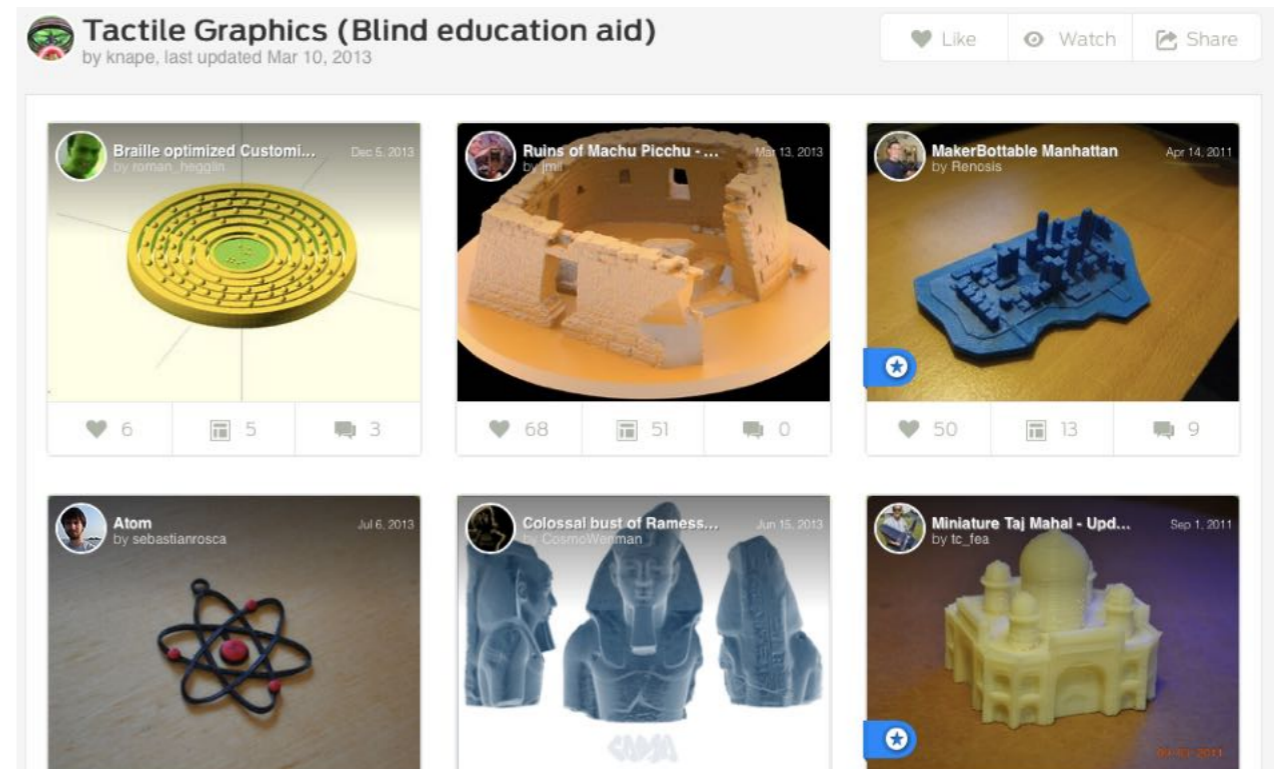
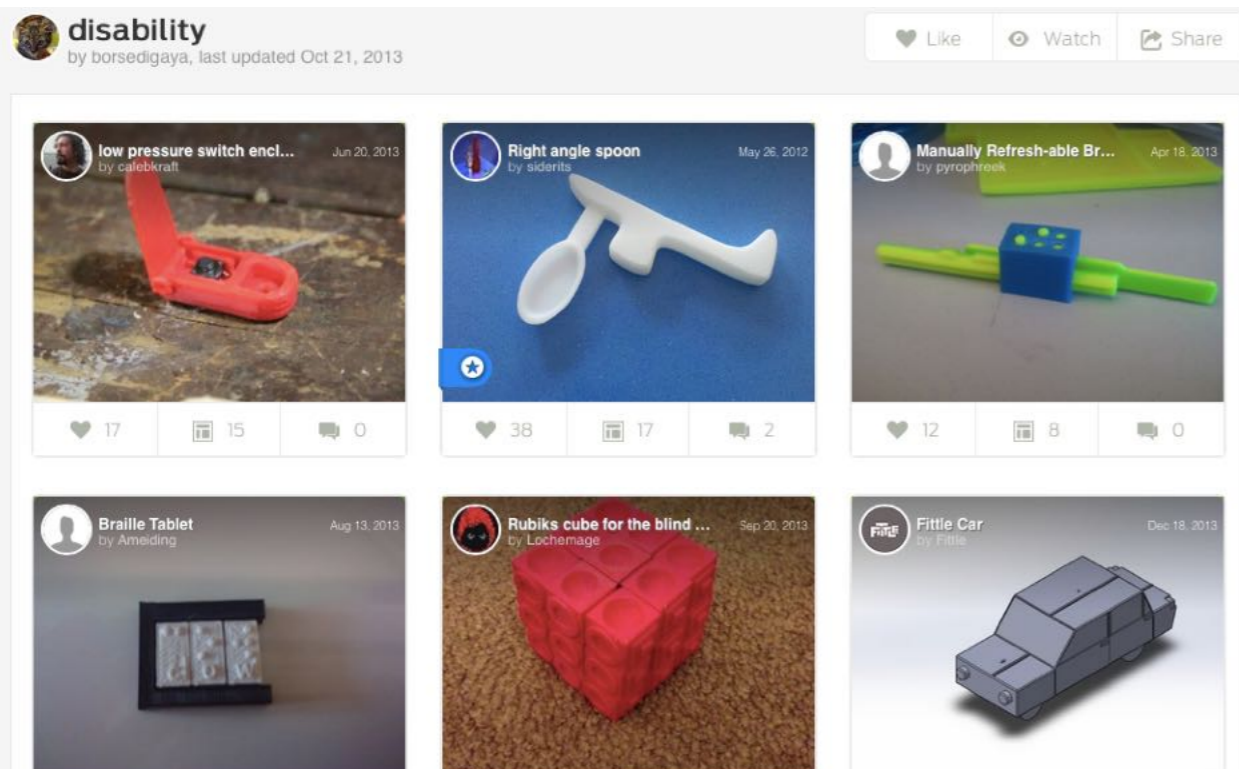
<http://www.thingiverse.com/thing:92937>



Movie from: <http://www.thingiverse.com/thing:44150>

# Collections of printable models from Thingiverse

- <http://www.thingiverse.com/borsedigaya/collections/disability/>
- <http://www.thingiverse.com/knape/collections/tactile-graphics-blind-education-aid/>



# Defcad

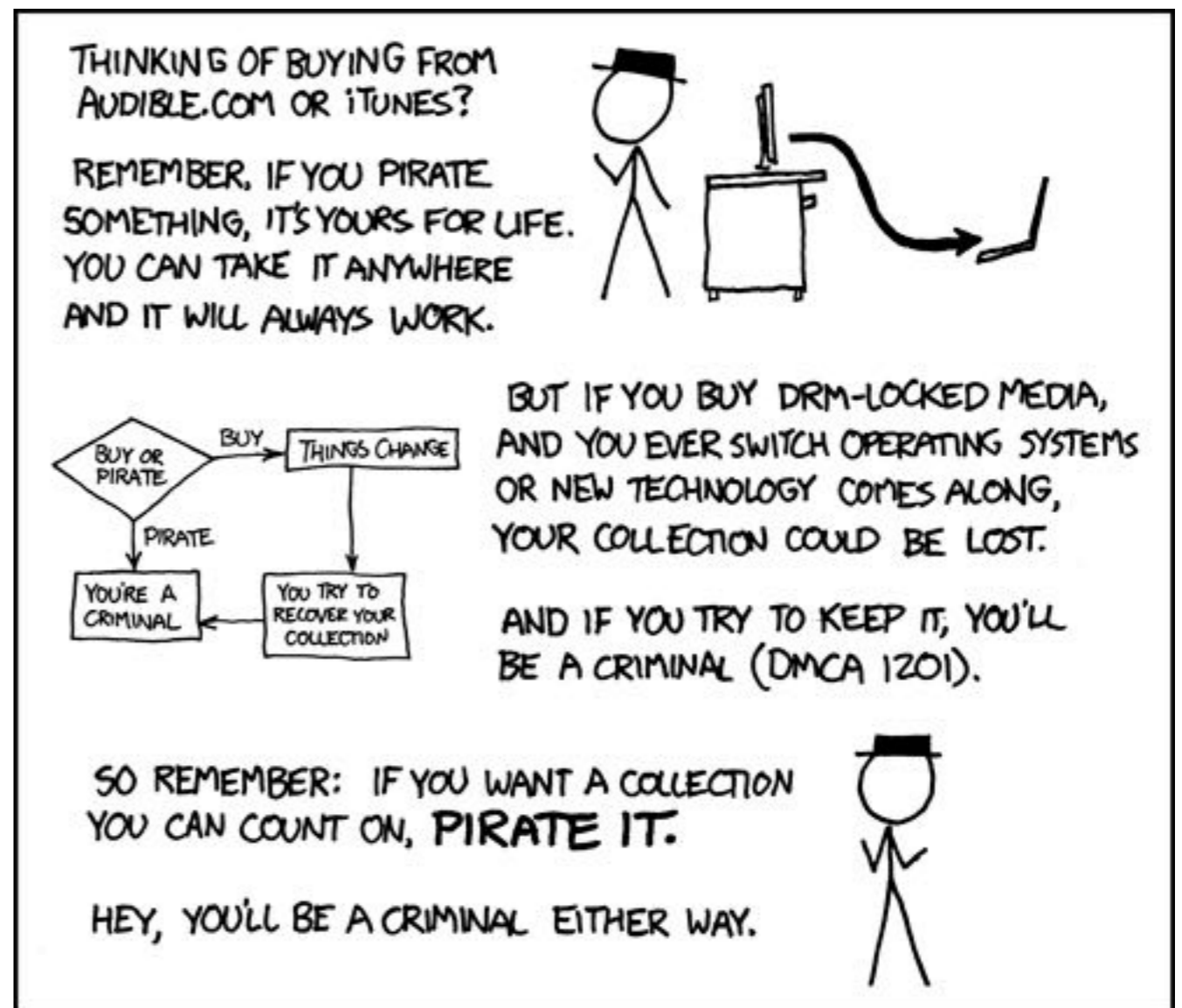
---



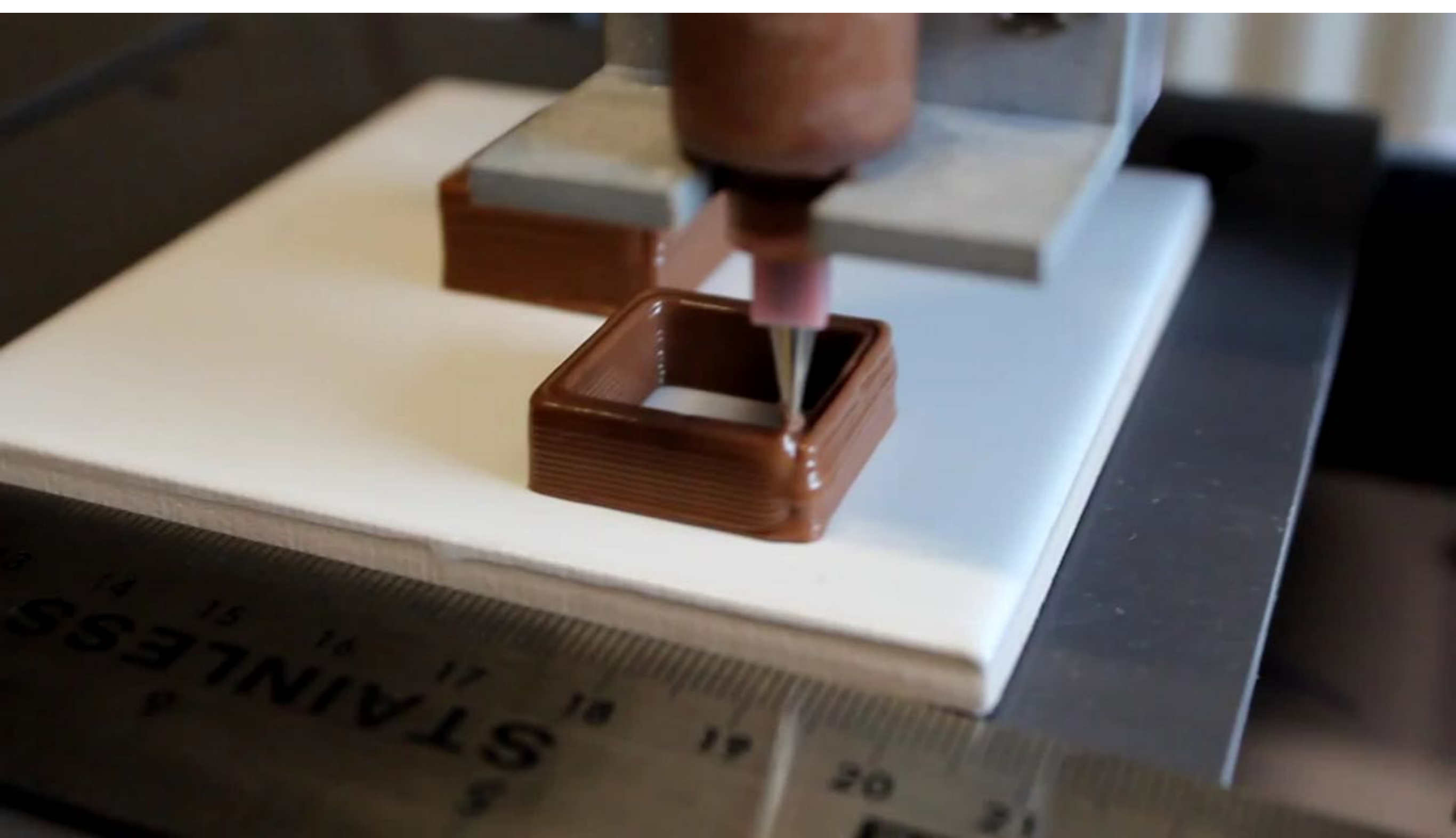
# DRM for 3D models?

---

- US patent [8286236](#), granted on 9 October to Intellectual Ventures of Bellevue, Washington, lends a 3D printer the ability to assess whether a computer design file it's reading has an authorisation code appended that grants access for printing. If it does not, the machine simply refuses to print - whether it's a solid object, a textile or even food that's being printed.



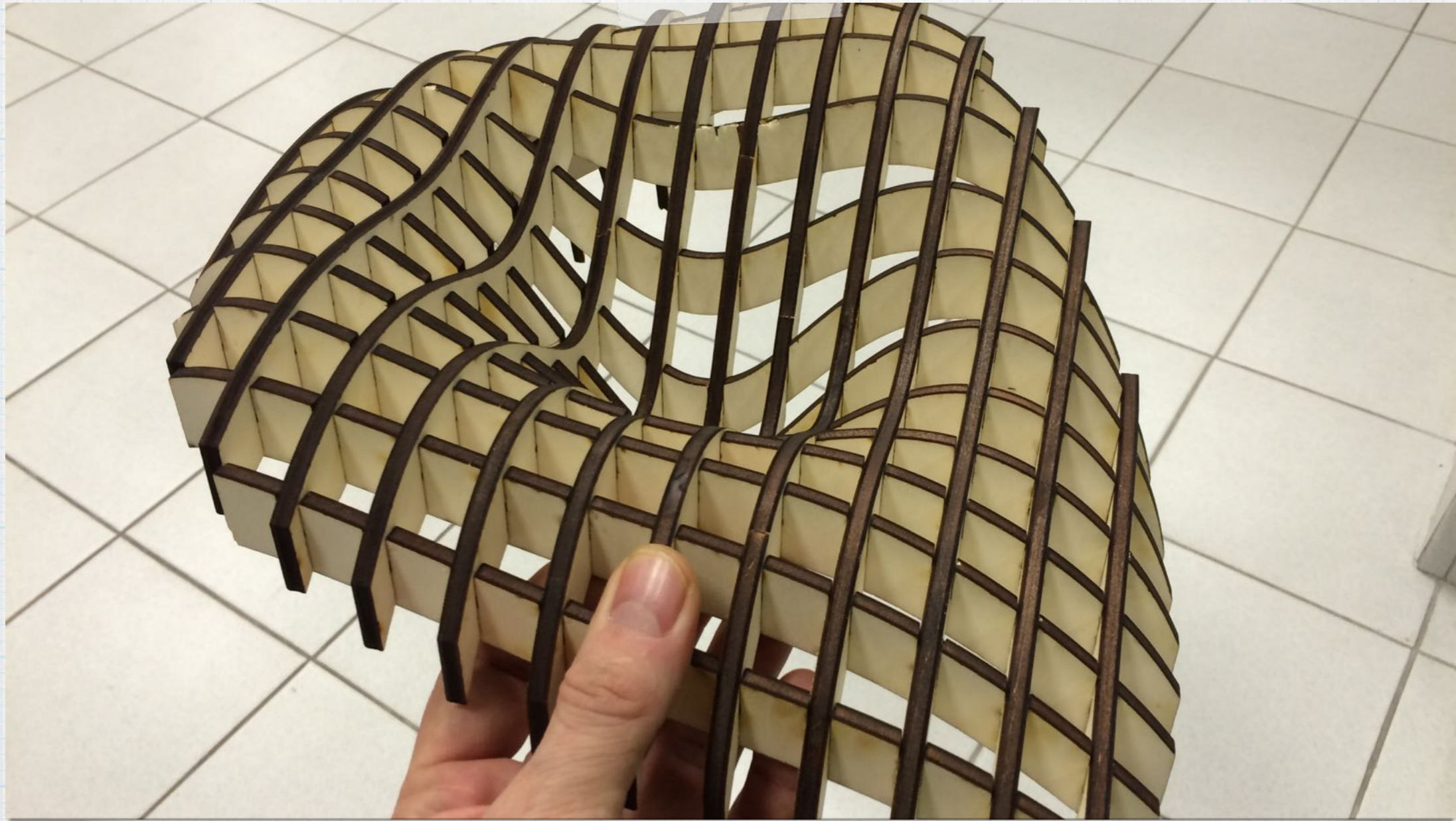
(IF YOU DON'T LIKE THIS, DEMAND DRM-FREE FILES)



Thank you for your patience ;-)  
Now break time!!!

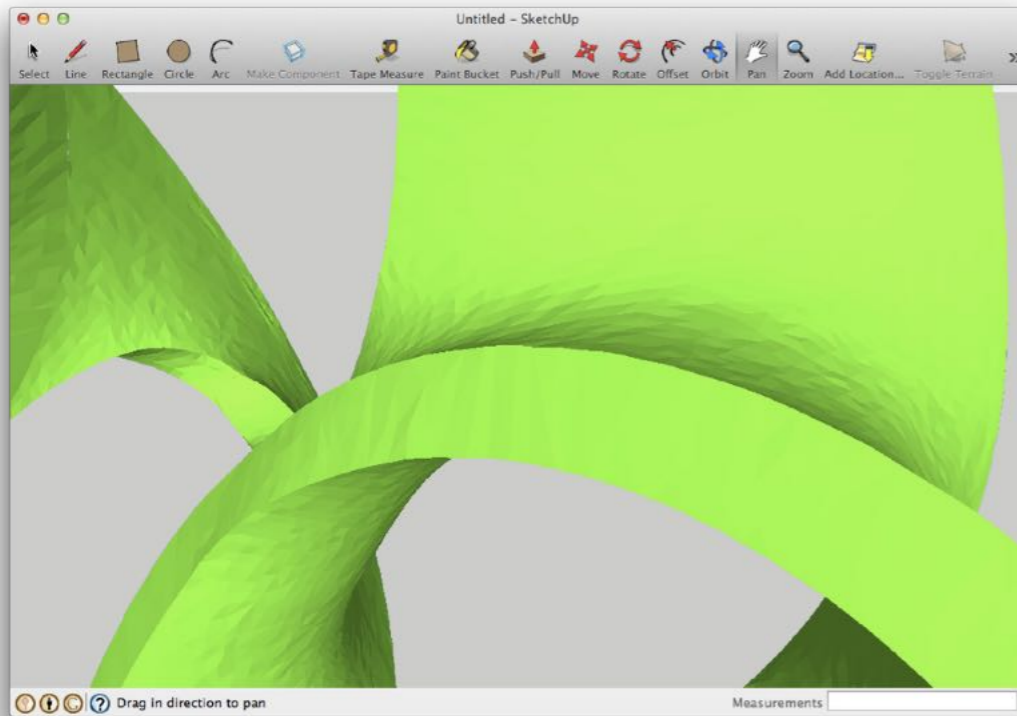
(Oh yes, 3D-printed chocolate! ;-)



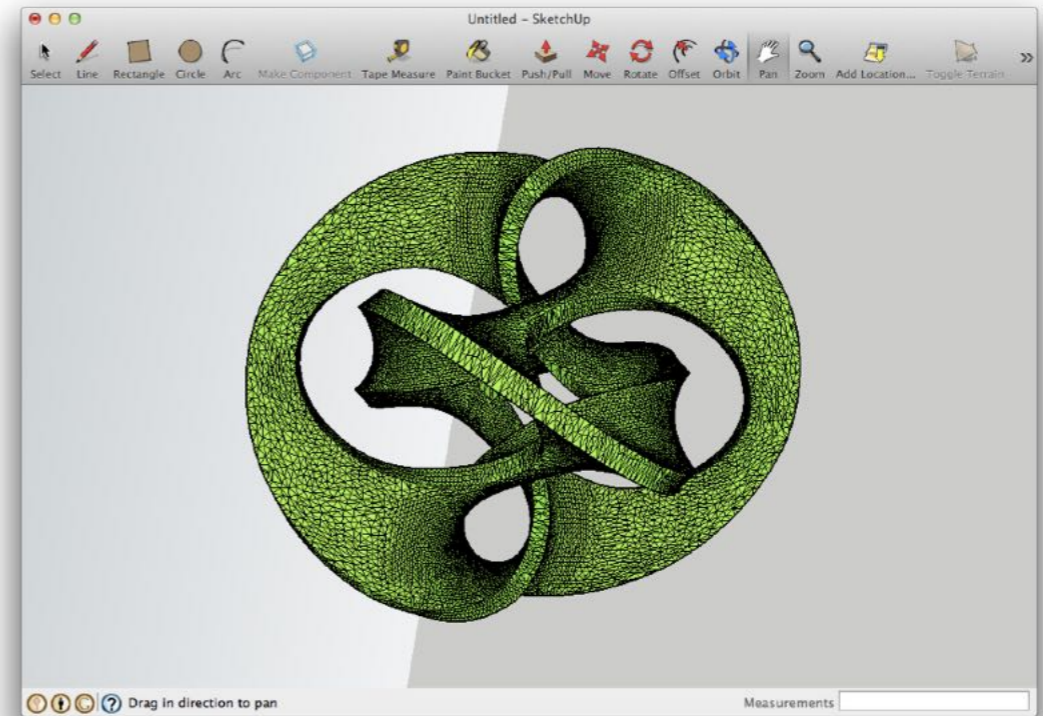


Mesh

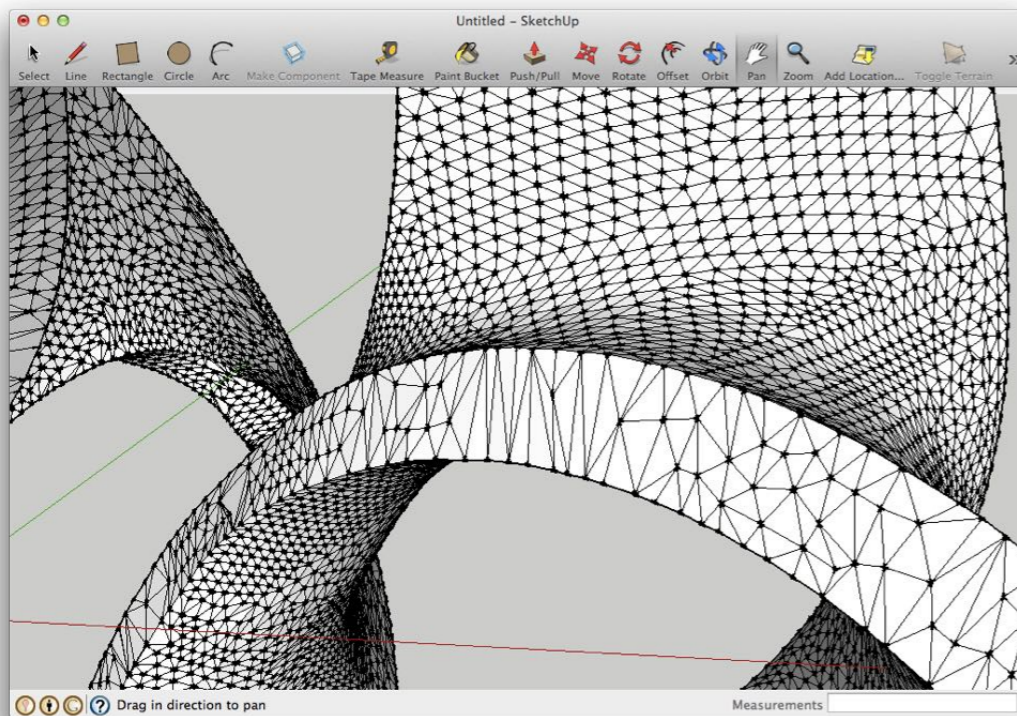
# 3D model (detail):



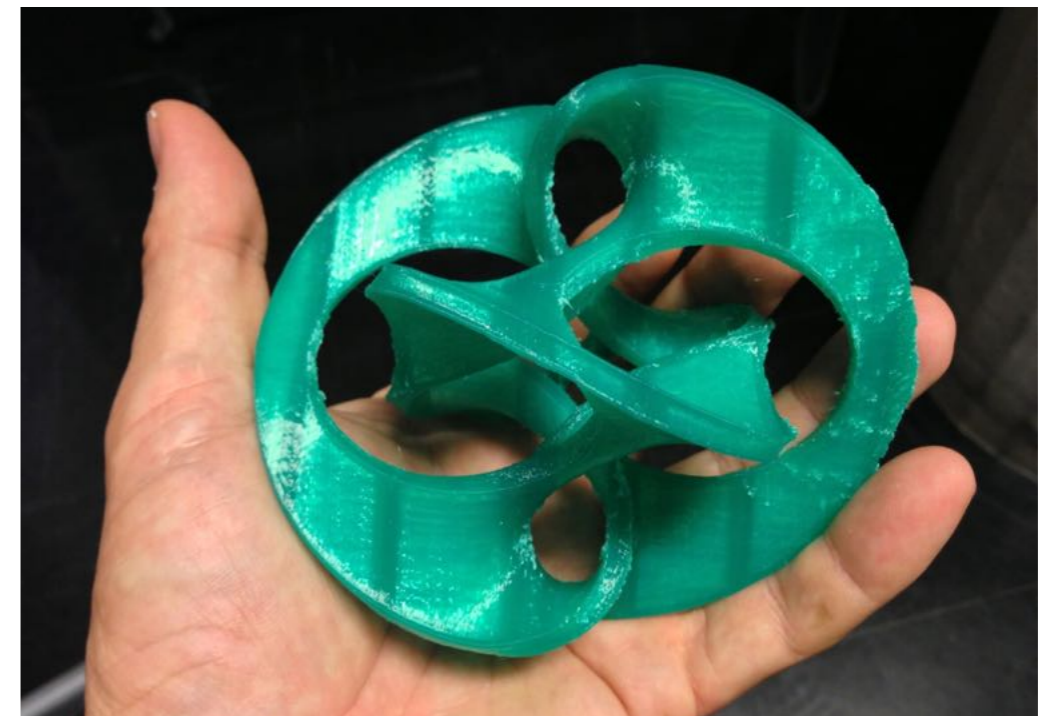
# 3D model, mesh:



# mesh (detail):



# printed object:



# 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:

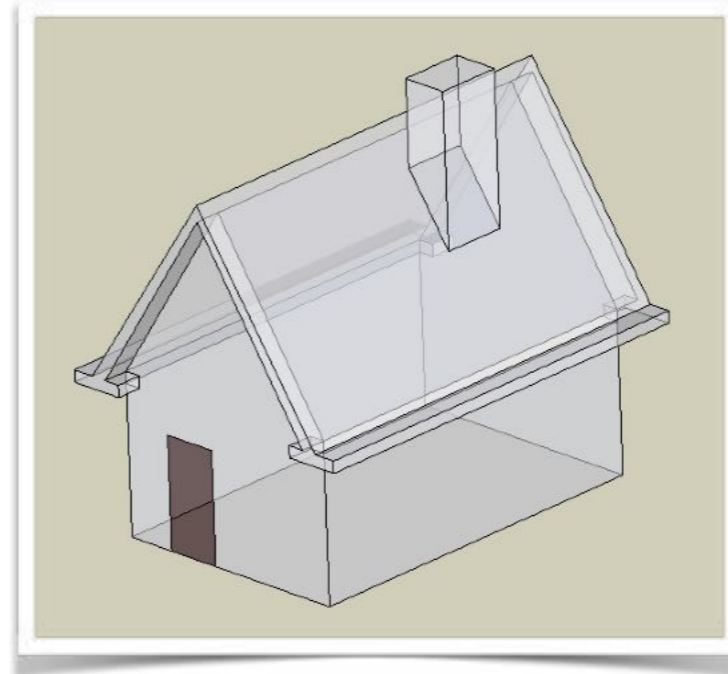
```
facet normal  $n_i$   $n_j$   $n_k$   
outer loop  
vertex  $v_{1x}$   $v_{1y}$   $v_{1z}$   
vertex  $v_{2x}$   $v_{2y}$   $v_{2z}$   
vertex  $v_{3x}$   $v_{3y}$   $v_{3z}$   
endloop  
endfacet
```

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]



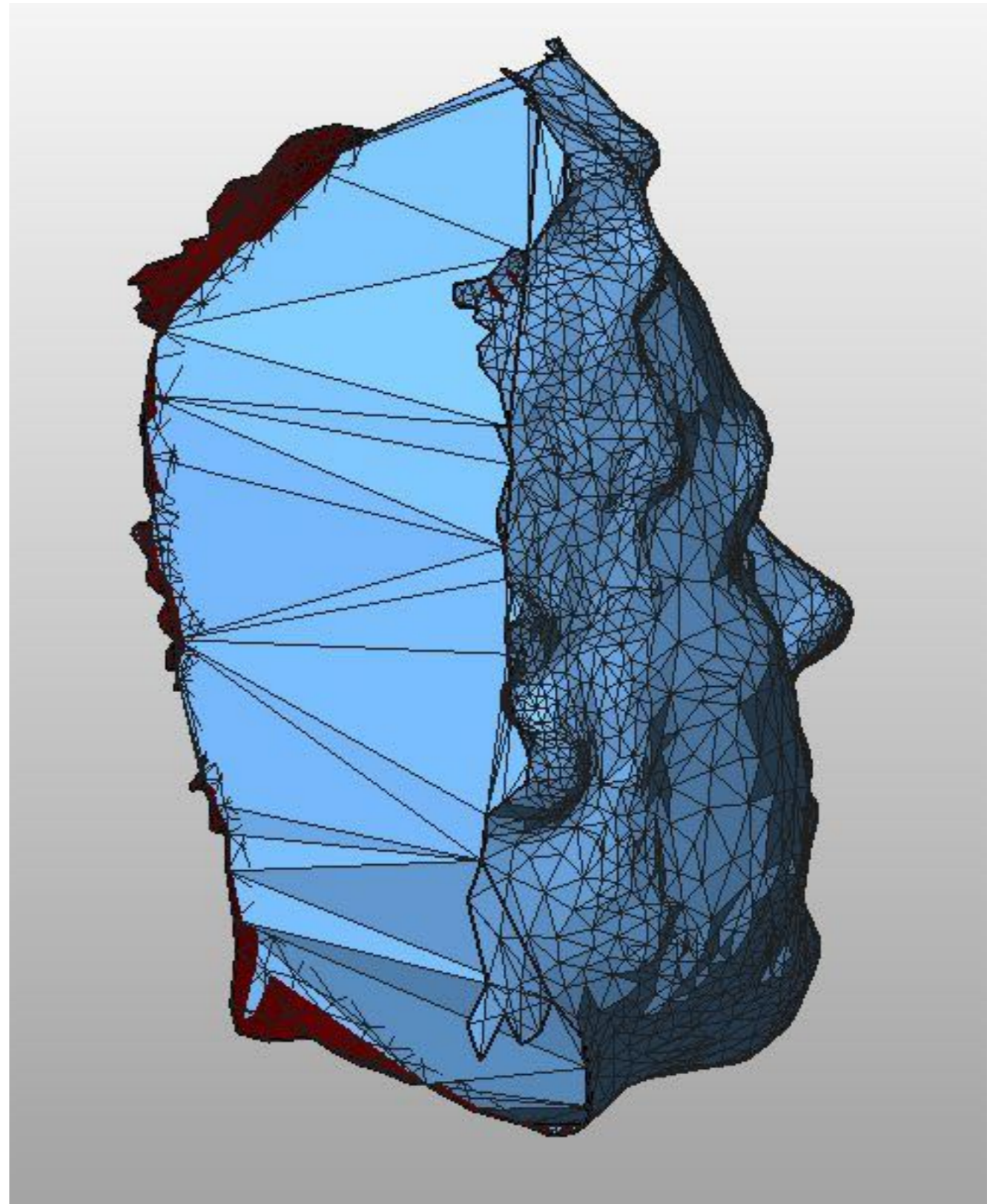
```
solid House  
facet normal 6.82119751824952e-17 -0.816496580927727 -0.577350269189624  
outer loop  
vertex 93660.6382456757 40.3376838970568 -161.045352763136  
vertex 92599.4905807017 244.743283455853 -450.118523884189  
vertex 92953.043971295 448.86742868779 -738.793658479011  
endloop  
endfacet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

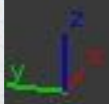
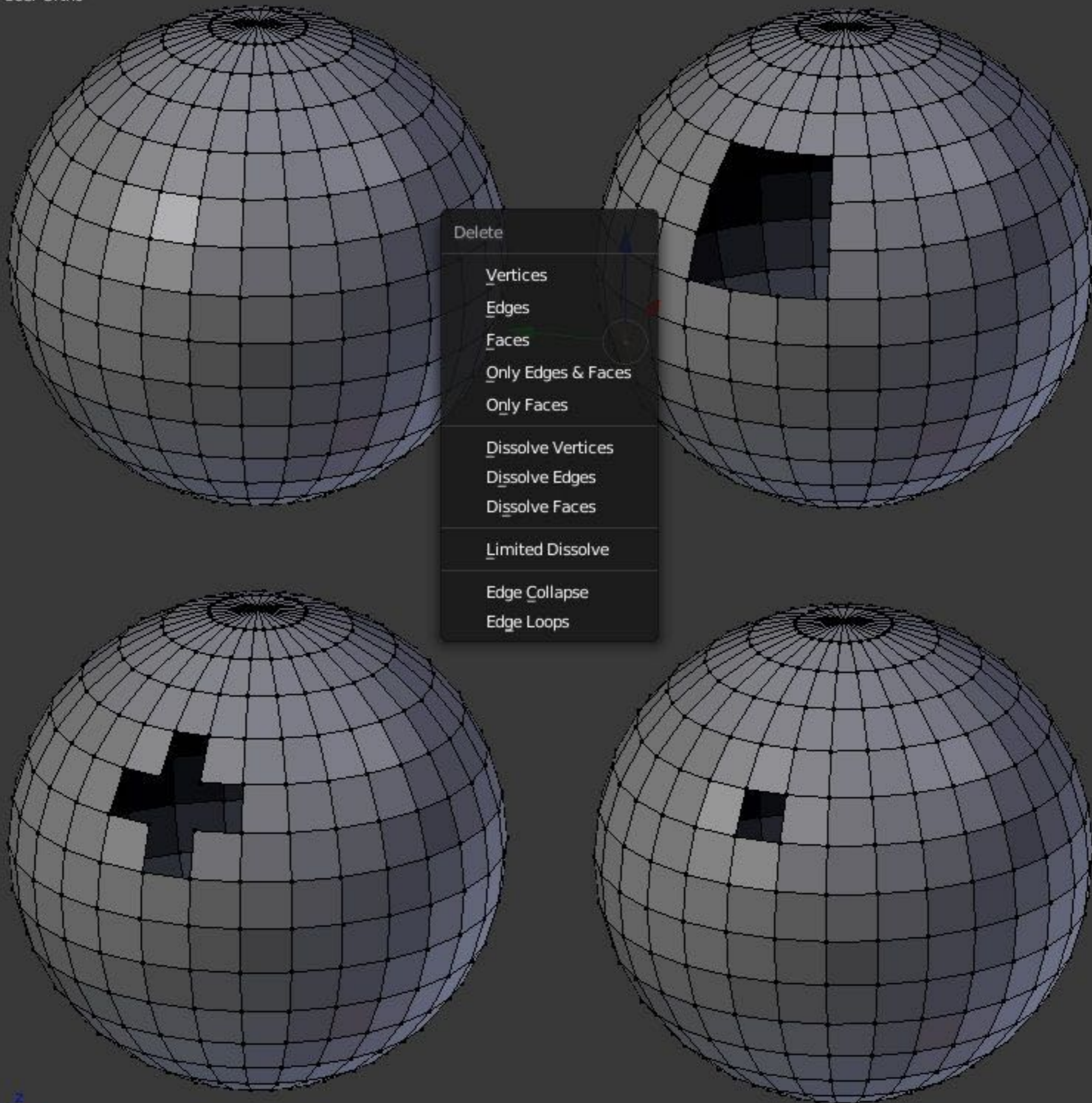
# Mesh requirements: watertightness

---

## Float, don't sink!

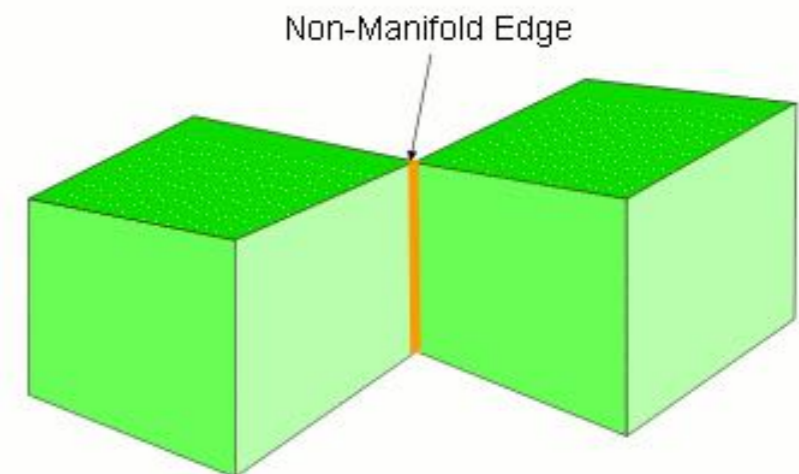
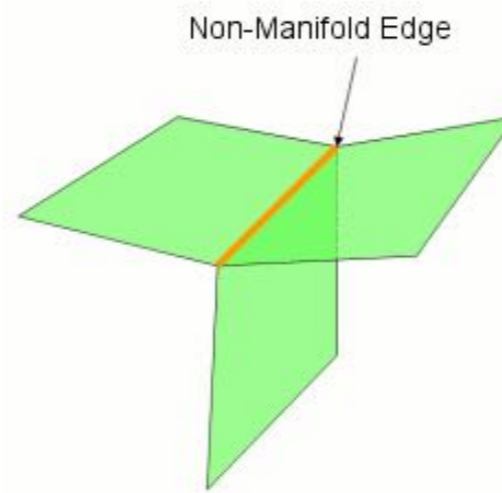
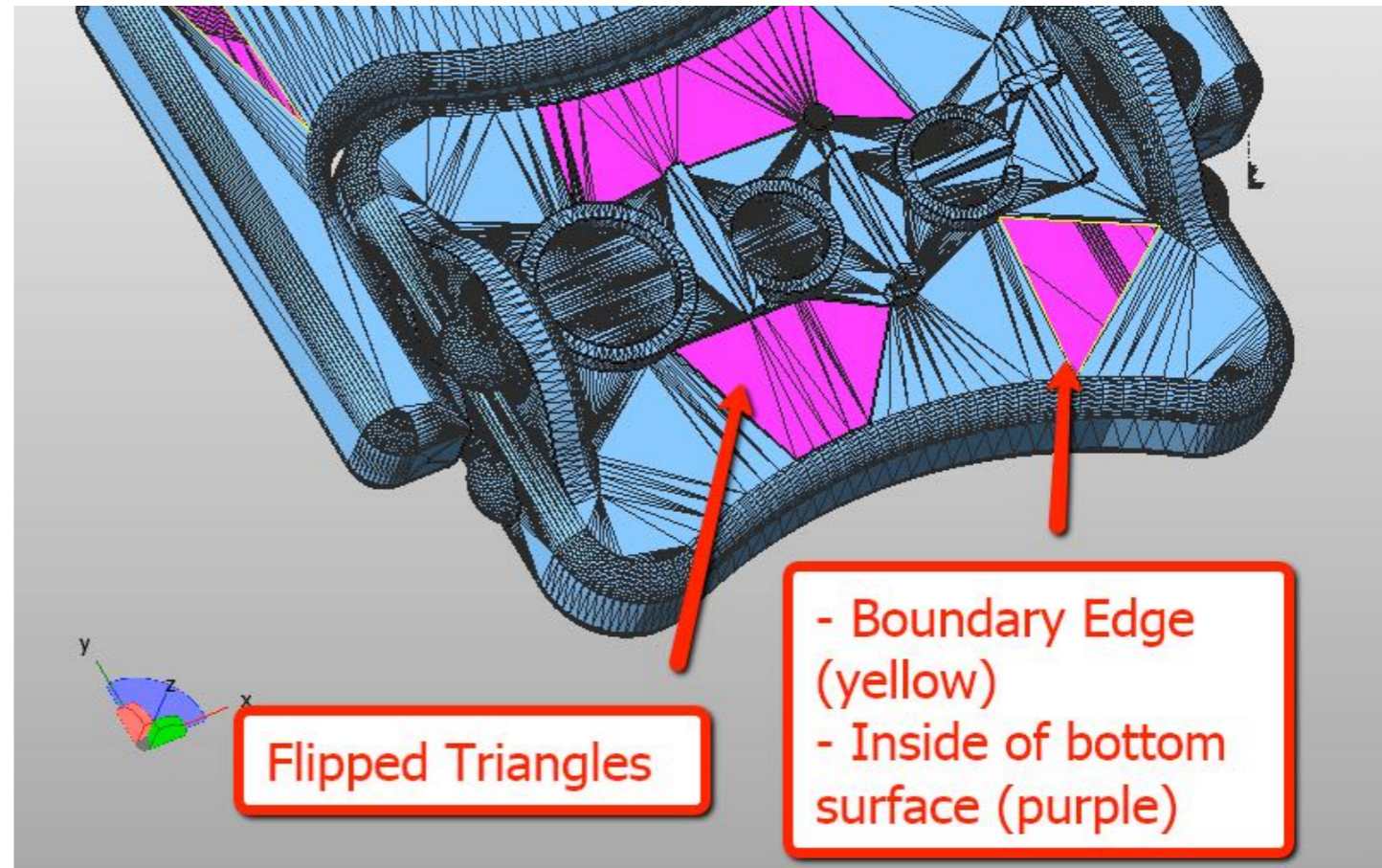
- È importante creare una **superficie “a tenuta d’acqua”** per il vostro modello, in modo che la stampante 3D sappia distinguere chiaramente l’interno (che deve essere riempito dal materiale di stampa) dall’esterno. In sunto, “a tenuta d’acqua” significa che **non ci sono buchi, fessure o parti mancanti nella superficie.**

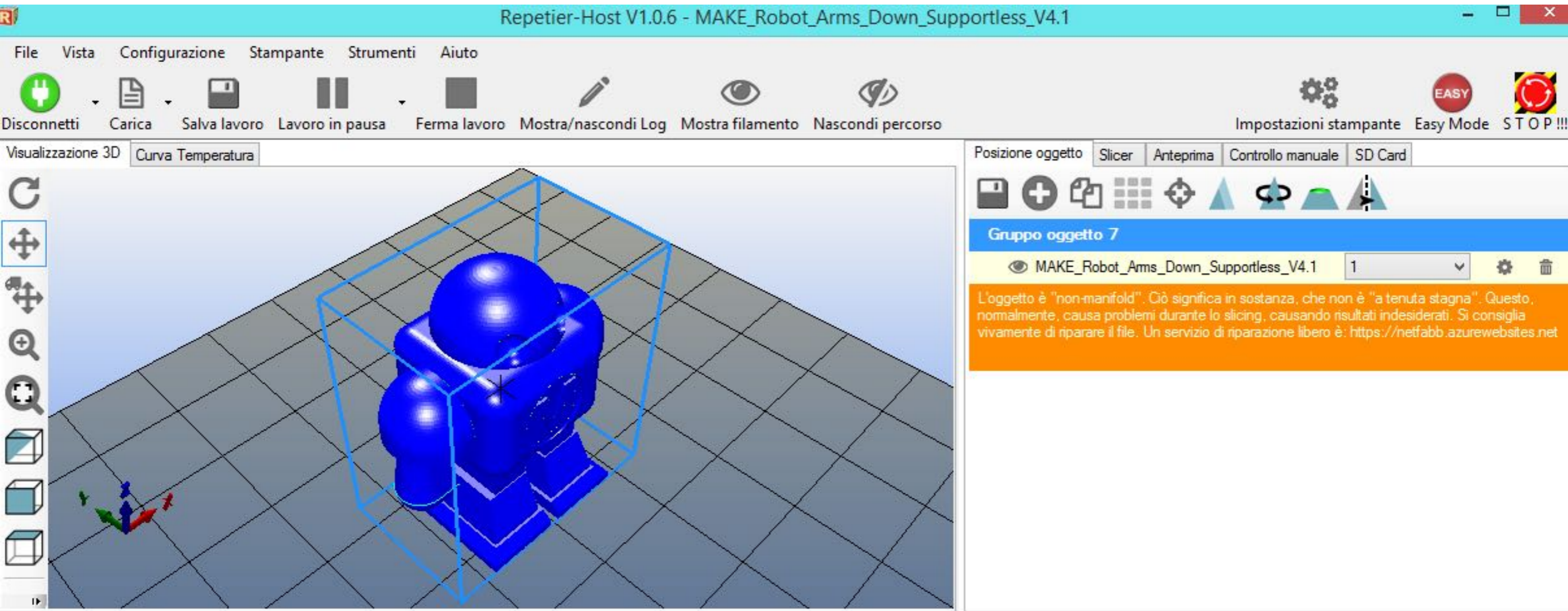




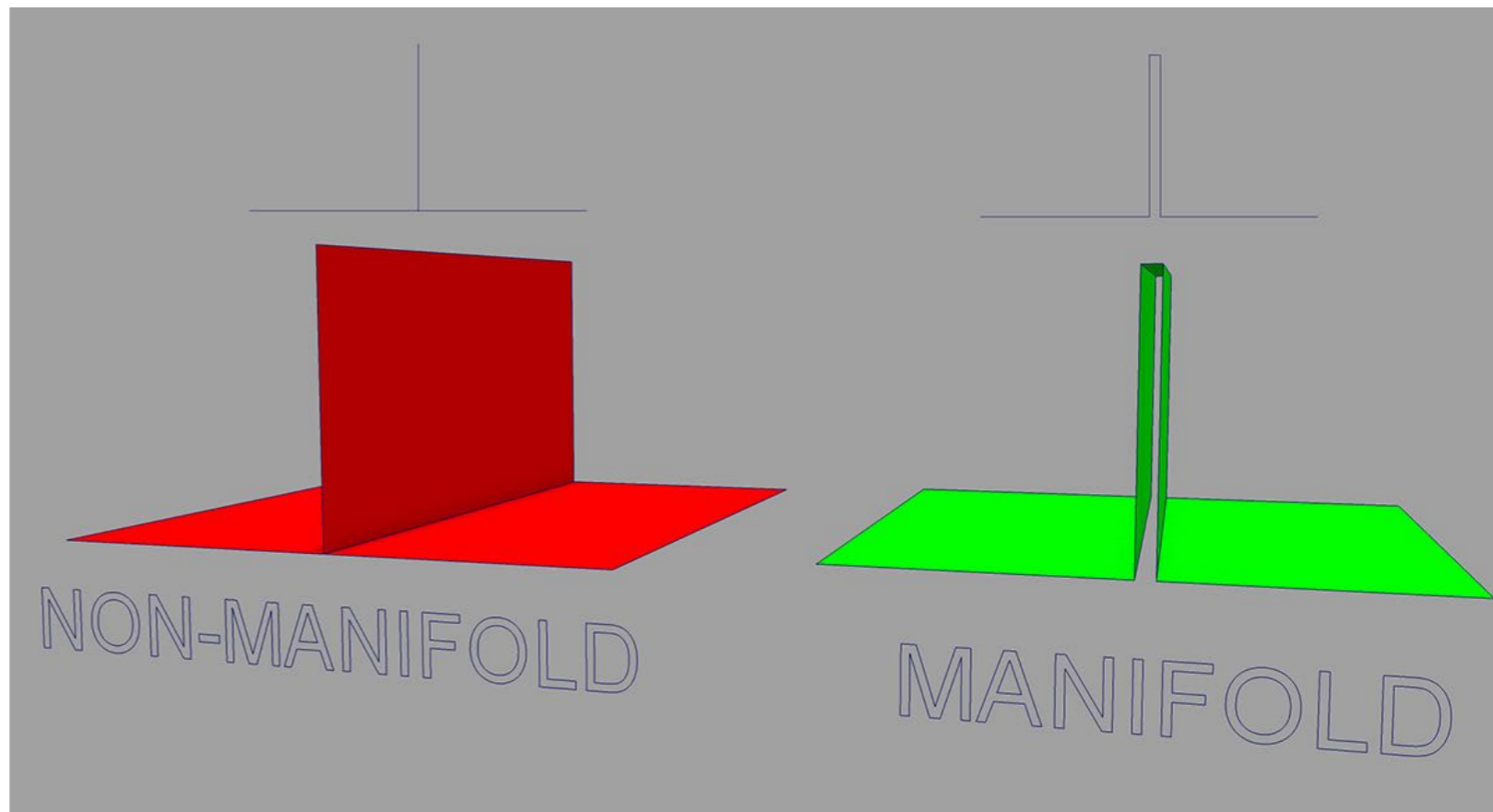
# Mesh requirements: flipped triangles

- Altra causa di problemi è una superficie che contiene dei **triangoli a faccia invertita**. Questi devono essere rovesciati per avere il corretto orientamento prima dello slicing.
- Devono anche esser eliminati i **punti “non-manifold”**, per esempio dove uno spigolo è condiviso da più facce.
- Altrimenti il software non riesce ad individuare un “dentro” e un “fuori” della mesh in maniera univoca.

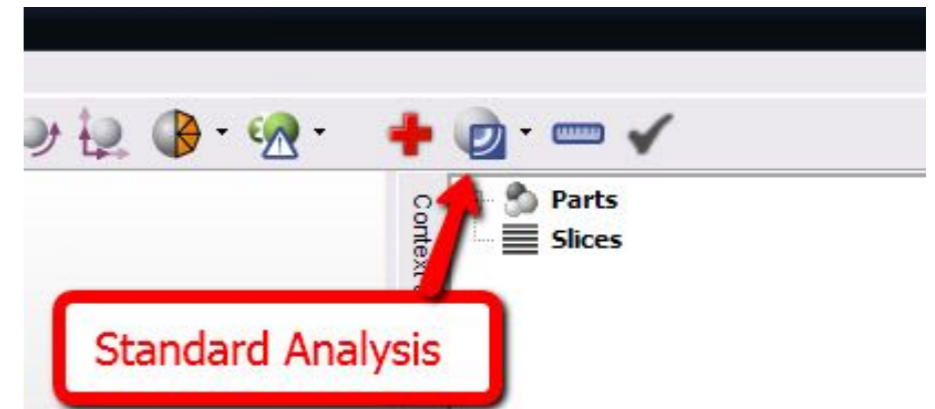
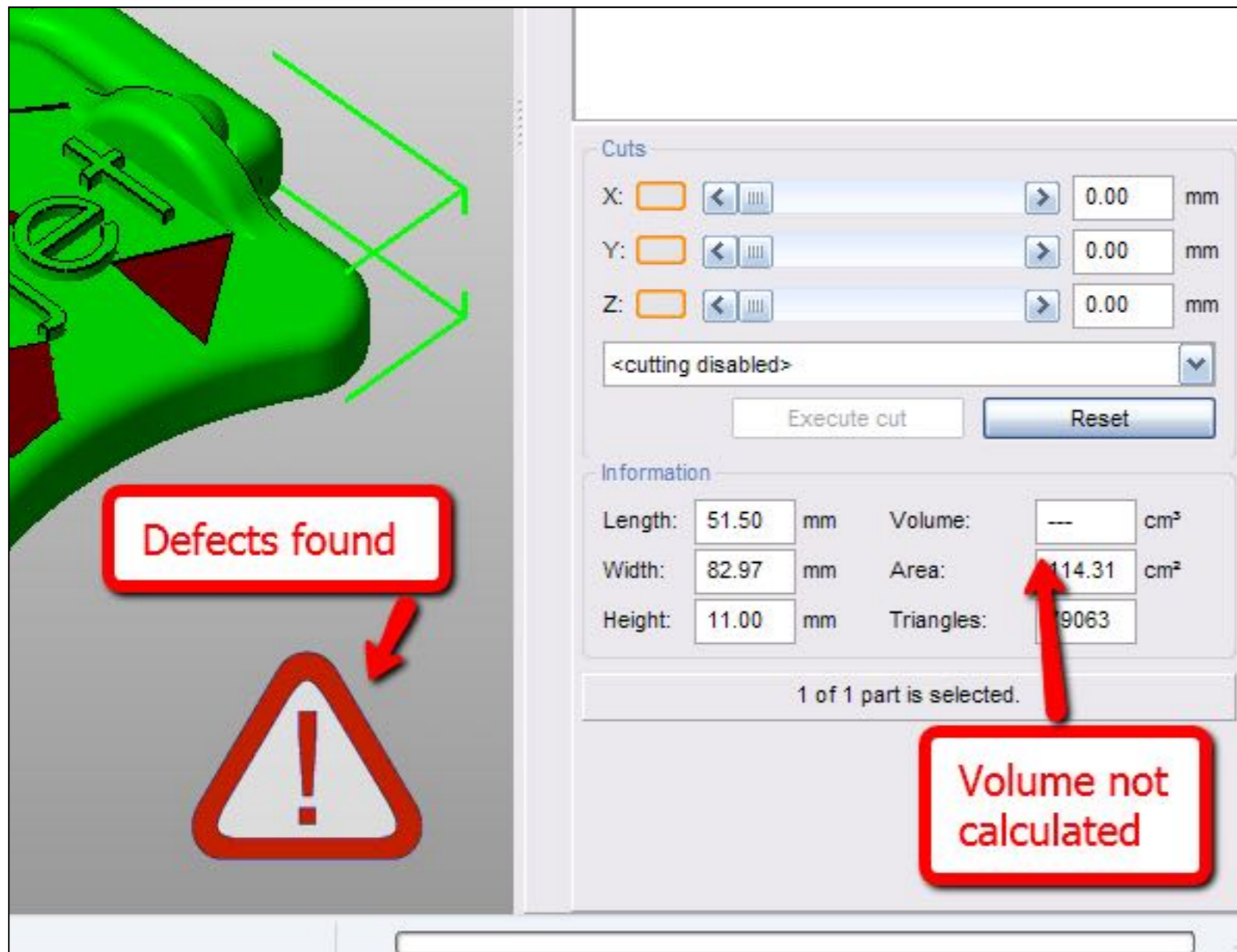




Warning!



# Netfabb



	X	Y	Z
Minimum:	21.19	25.50	29.50
Maximum:	72.68	108.48	40.50
Size:	51.50	82.97	11.00

Volume:	19.2874 cm <sup>3</sup>	Area:	114.3135 cm <sup>2</sup>
Points:	39537	Edges:	118599
Triangles:	79063	Shells:	5
Holes:	3	Bad edges:	0
Boundary edges:	9	Boundary Len:	69.57 mm
Flipped triangles:	51		

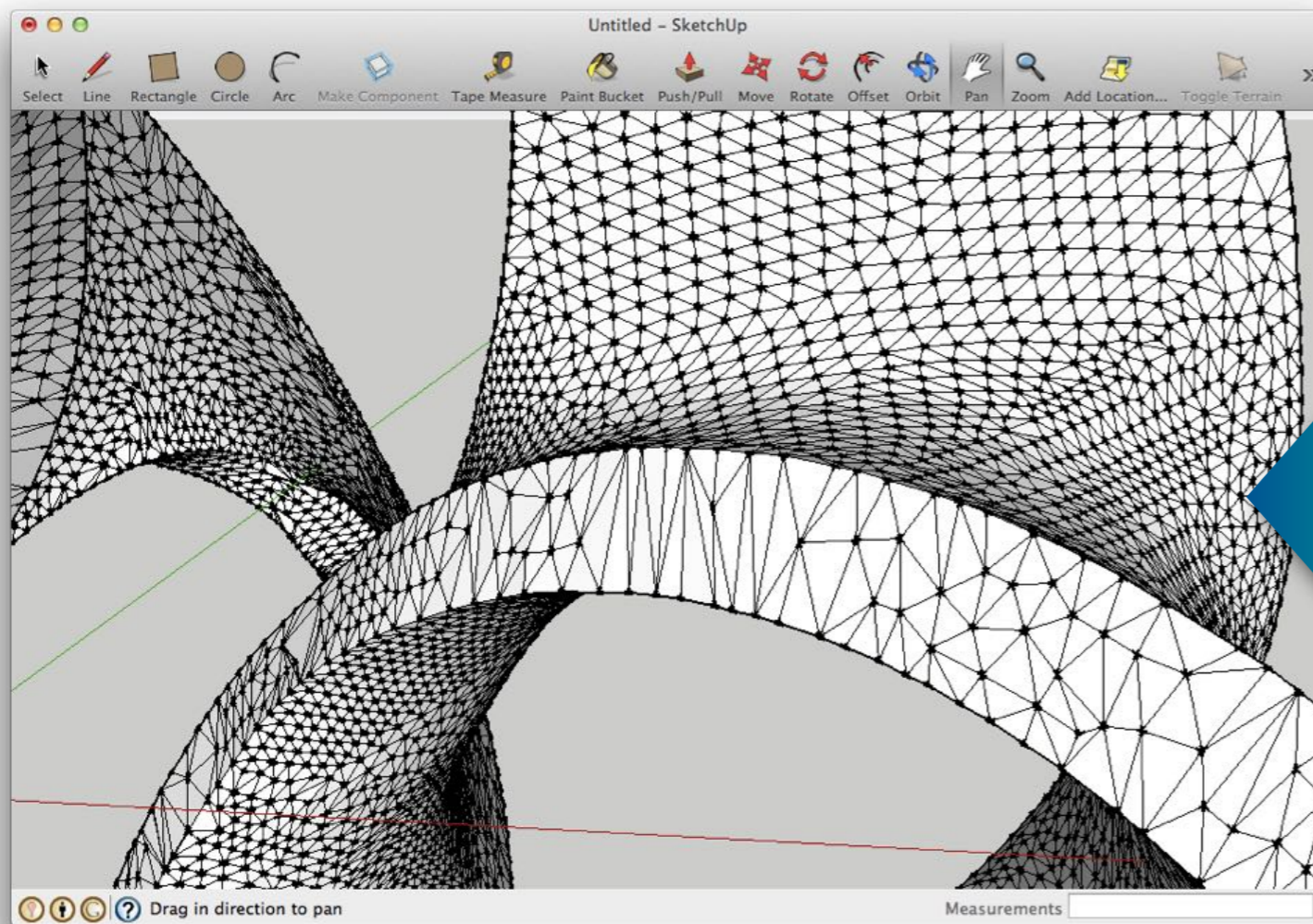
Surface is closed:	No
Surface is orientable:	Yes

	Min:	Max:	Ø:	Dev:
Edges/Point	3.00	45.00	6.00	0.81
Triangles/Edge	1.00	2.00	2.00	0.01
Triangle Quality	0.00	1.00	0.63	0.21





Slicing

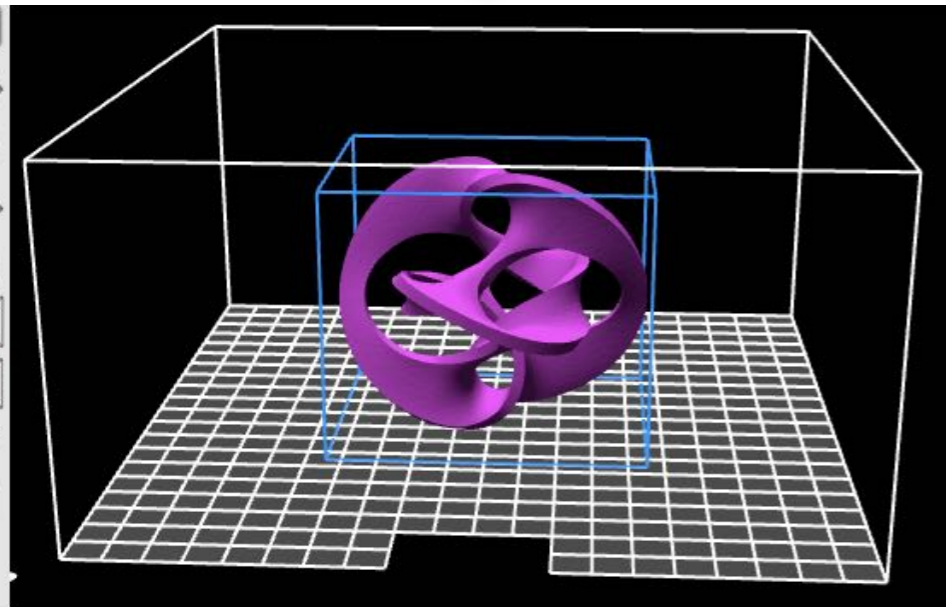


```
1109 S200 ; wait for temperature to be reached
;90 ; use absolute coordinates
;21 ; set units to millimeters
G92 E0
M82 ; use absolute distances for extrusion
G1 F1800.000 E-1.00000
G1 Z0.630
G92 E0
G1 X111.025 Y108.686 F7200.000
G1 Z0.330
G1 F1800.000 E1.00000
G1 X110.405 Y108.956 F900.000 E1.02268
G1 X109.765 Y109.196 E1.04559
G1 X108.785 Y109.476 E1.07977
G1 X107.785 Y109.666 E1.11390
G1 X106.775 Y109.766 E1.14793
G1 X106.095 Y109.776 E1.17074
G1 X105.075 Y109.726 E1.20498
G1 X101.345 Y109.356 E1.33066
G1 X100.665 Y109.266 E1.35366
G1 X99.995 Y109.136 E1.37655
G1 X99.335 Y108.966 E1.39940
G1 X98.685 Y108.756 E1.42231
G1 X97.745 Y108.376 E1.45630
G1 X96.835 Y107.906 E1.49065
G1 X96.255 Y107.546 E1.51354
G1 X95.425 Y106.936 E1.54808
G1 X94.655 Y106.266 E1.58230
G1 X93.955 Y105.526 E1.61646
G1 X93.315 Y104.726 E1.65081
```

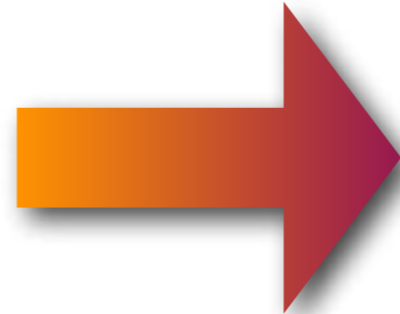
The conversion from mesh (3D model, STL/OBJ format) to gcode (instructions for the 3D printer) is called “slicing” (in italiano si può tradurre con: *l'azione di “affettare” l'oggetto*)

```
solid vcg
facet normal 1.644528e-01 9.728446e-01 -1.628764e-01
  outer loop
    vertex -2.251450e+01 -1.116070e+01 1.606290e+01
    vertex -2.335270e+01 -1.109470e+01 1.561080e+01
    vertex -2.328920e+01 -1.096510e+01 1.644900e+01
  endloop
endfacet
facet normal -1.989384e-01 2.022959e-01 -9.589056e-01
  outer loop
    vertex -1.090160e+01 5.158700e+00 2.825740e+01
    vertex -1.032000e+01 5.417800e+00 2.819140e+01
    vertex -9.804300e+00 4.709100e+00 2.793490e+01
  endloop
endfacet
facet normal -8.213068e-01 -5.629737e-01 9.228100e-02
  outer loop
    vertex -9.804300e+00 -2.974080e+01 2.793490e+01
```

STL (vertexes)

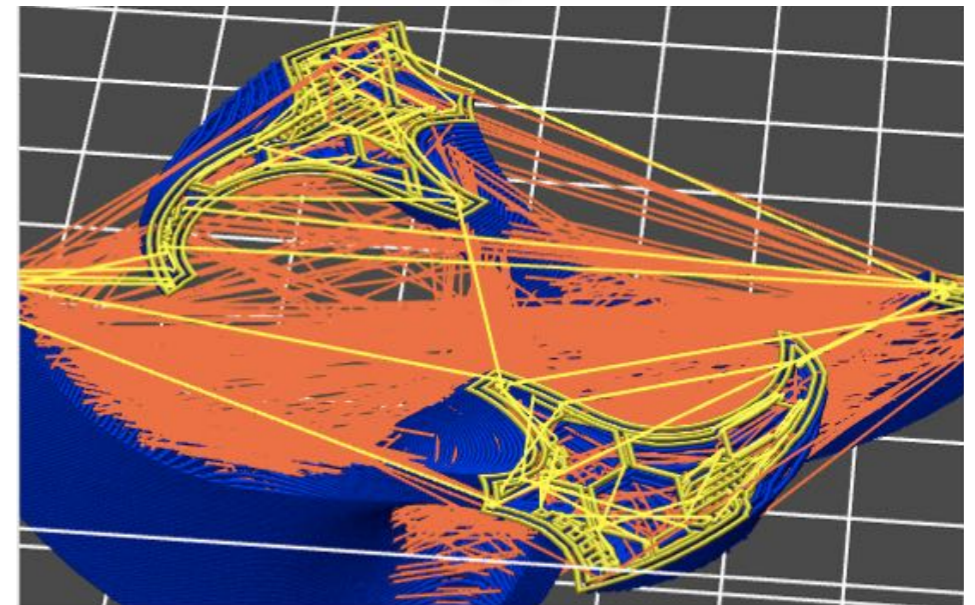


3D model



```
!109 S200 ; wait for temperature to be reached
;J90 ; use absolute coordinates
G21 ; set units to millimeters
G92 E0
M82 ; use absolute distances for extrusion
G1 F1800.000 E-1.00000
G1 Z0.630
G92 E0
G1 X111.025 Y108.686 F7200.000
G1 Z0.330
G1 F1800.000 E1.00000
G1 X110.405 Y108.956 F900.000 E1.02268
G1 X109.765 Y109.196 E1.04559
G1 X108.785 Y109.476 E1.07977
G1 X107.785 Y109.666 E1.11390
G1 X106.775 Y109.766 E1.14793
G1 X106.095 Y109.776 E1.17074
G1 X105.075 Y109.726 E1.20498
G1 X101.345 Y109.356 E1.33066
```

g-code (printing instructions)



path of the printing head



netfabb Pro



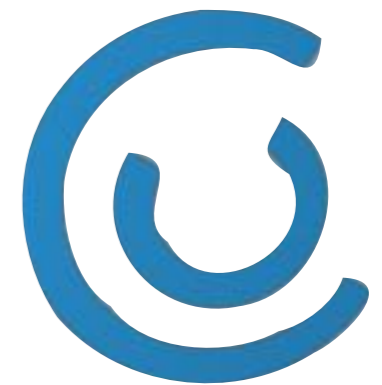
Slic3r



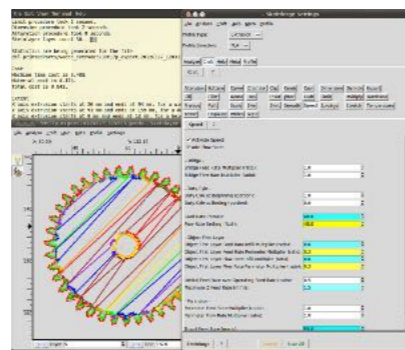
Cura



MakerWare



Craftware



Skeinforge



KISSlicer



# Slic3r

Slic3r

Plater | Print Settings | Filament Settings | Printer Settings

Add... Delete Delete All Arrange More Fewer 45° ccw 45° cw Rotate... Scale... Split View/Cut... Settings...

Name	Copies	Scale
Gecko_Headphone...	1	100%

Print settings: simple 15infillgross... ▾

Filament: PLA 1,77 220 ▾

Printer: simple ▾

Export G-code...

Export STL...

Y = 50

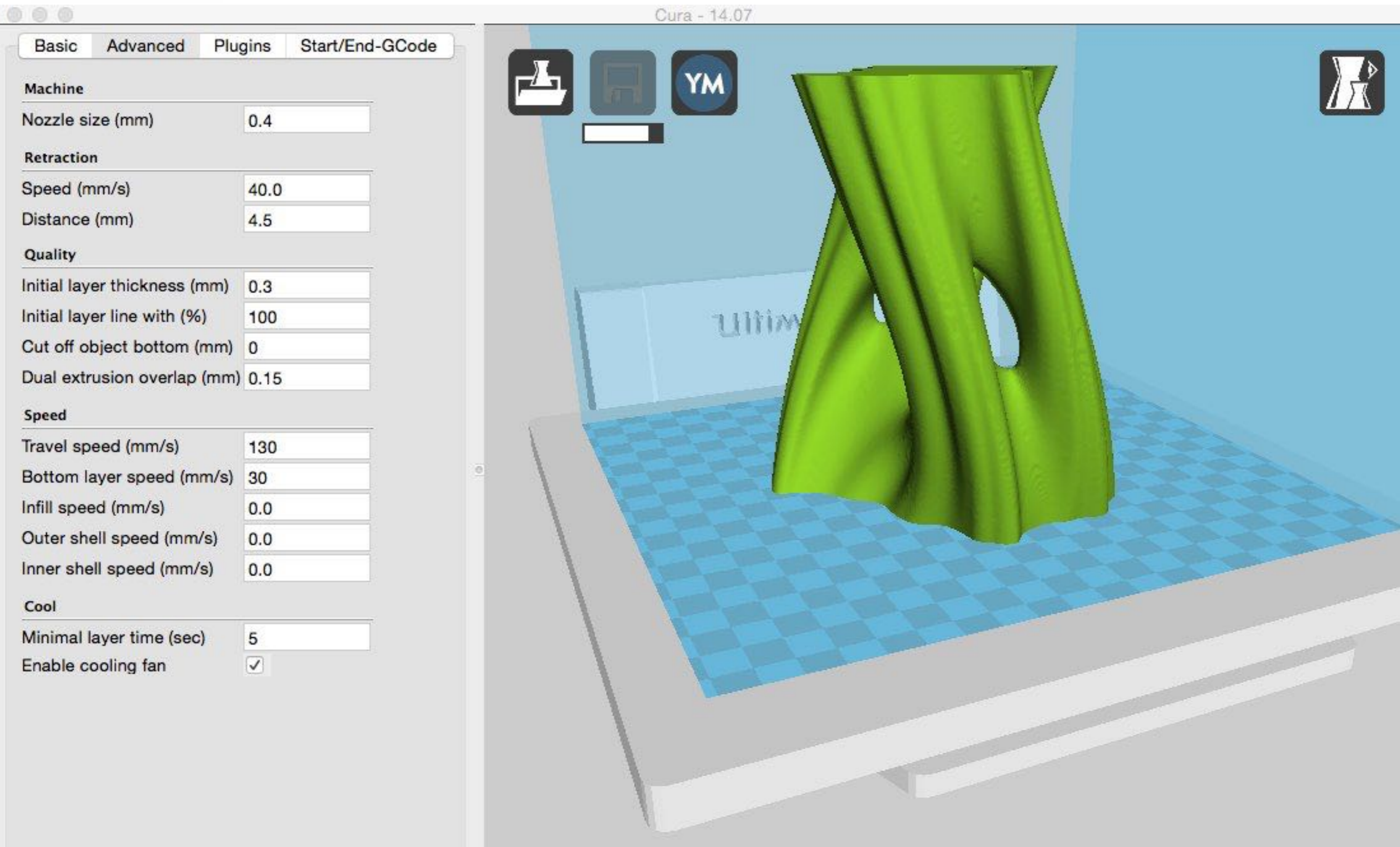
X = 50

Info

Size:	101.29 x 48.78 x 2.50	Volume:	5675.99
Facets:	3228 (1 shells)	Materials:	1
Manifold:	⚠ Auto-repaired (4163 errors)		

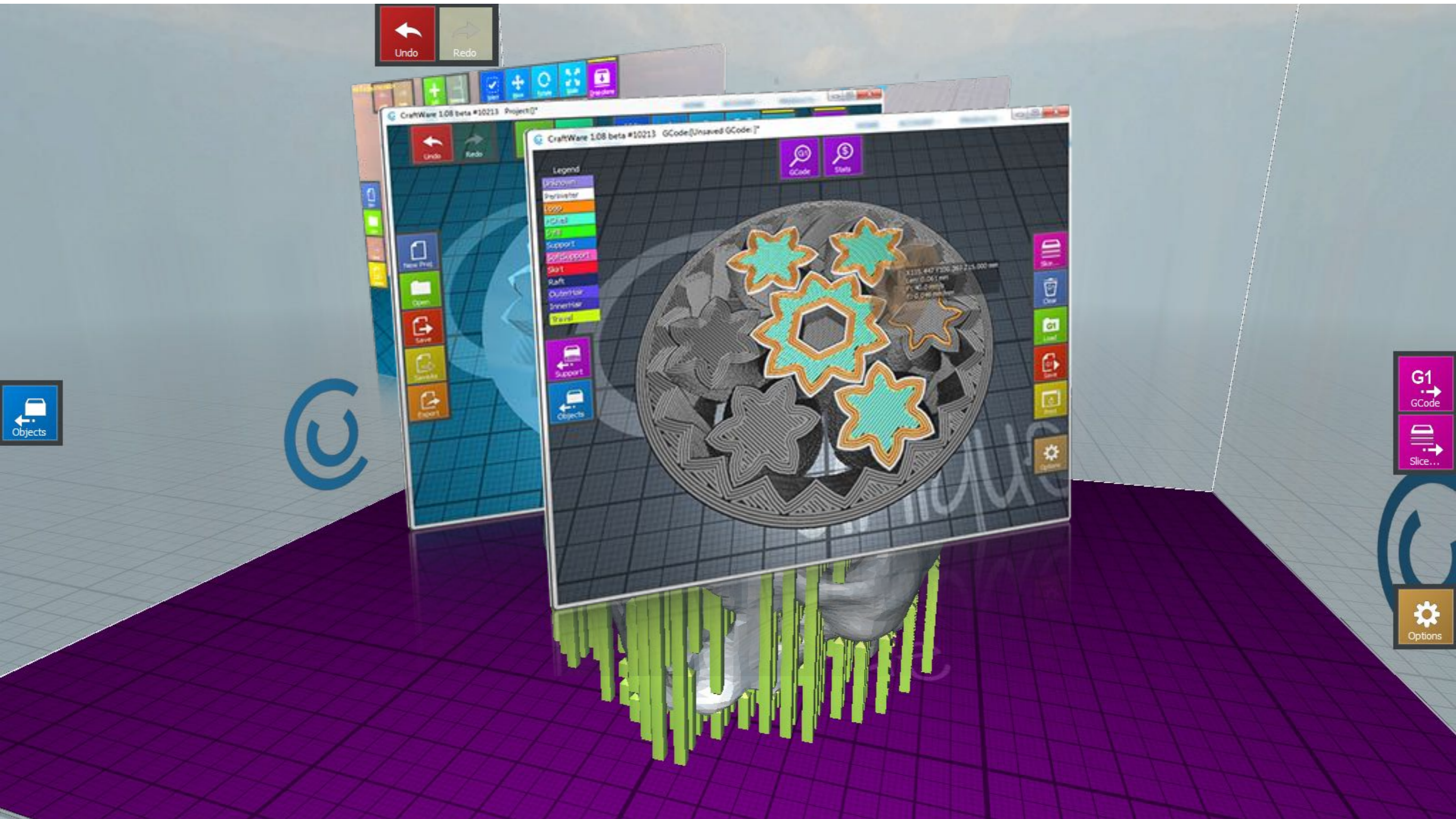


# Cura

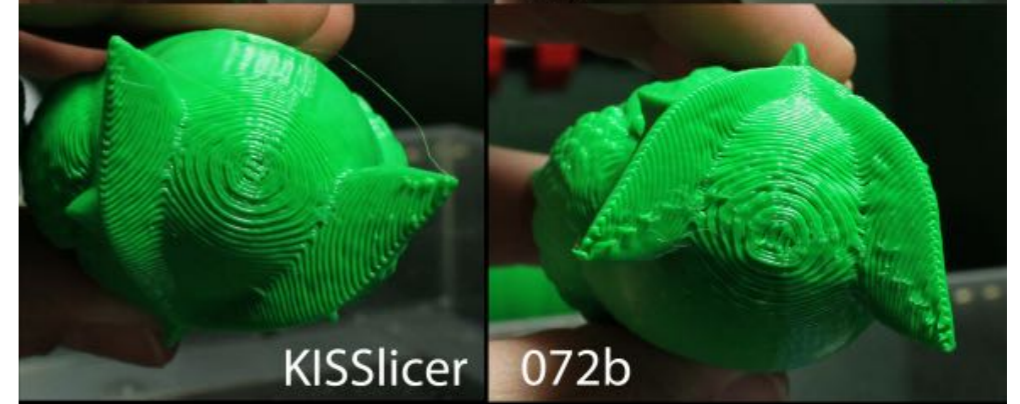
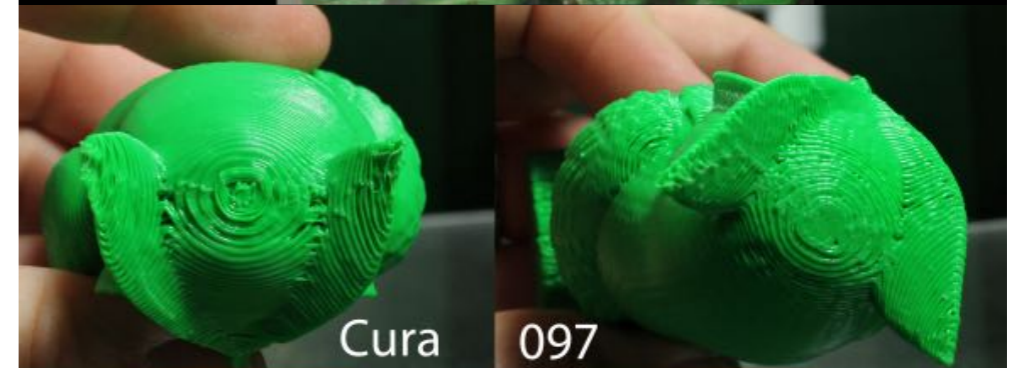
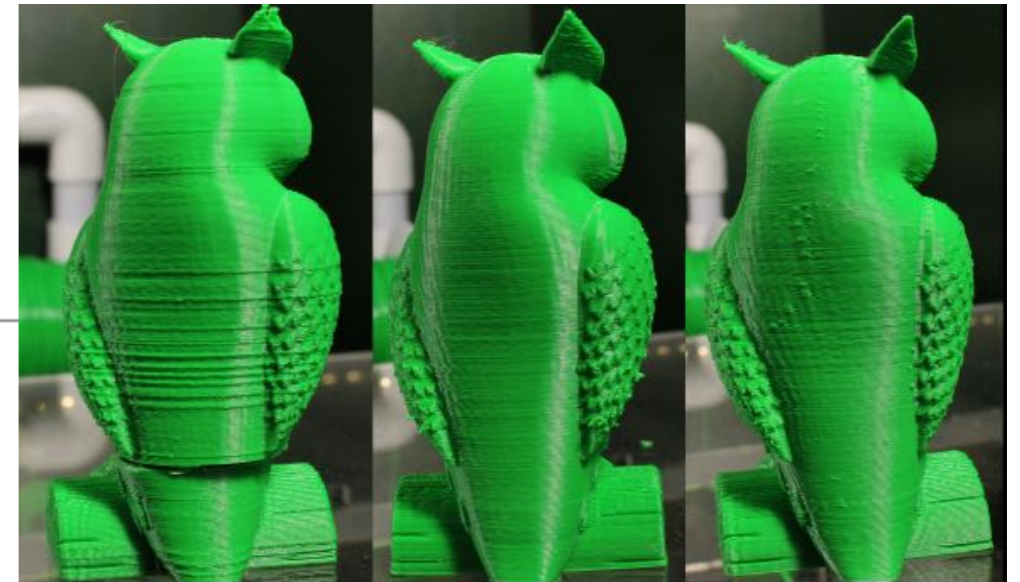




# CraftWare

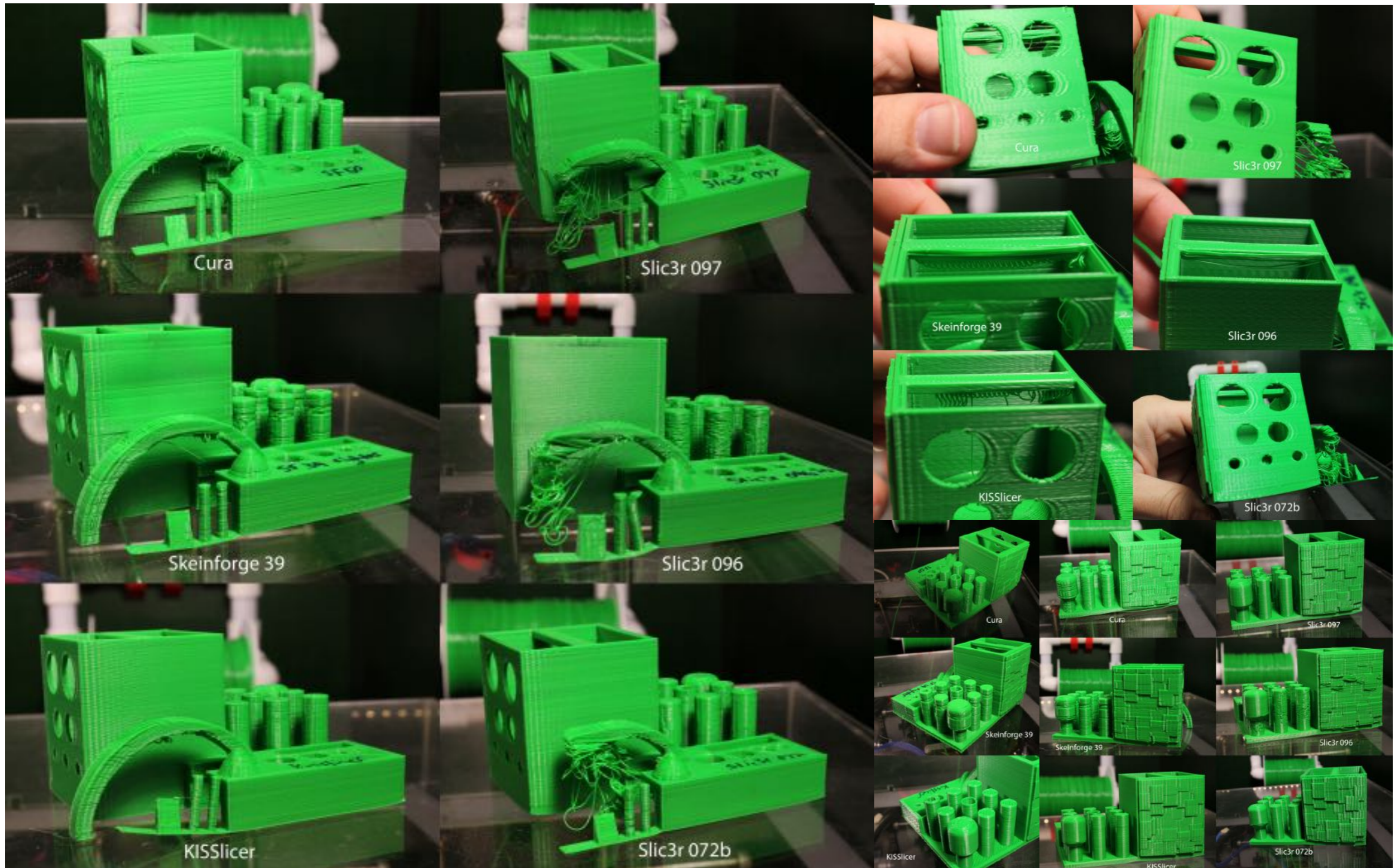


# Slicing: arte, scienza, e ...mal di pancia ;-)





Soluzione: fare molte prove e confrontare i risultati





# Common issues

Photo from: "The art of 3D print failure"

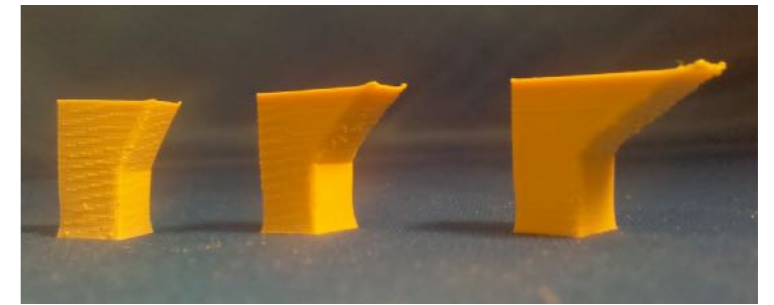
<https://www.flickr.com/groups/3d-print-failures/>

# Model issues

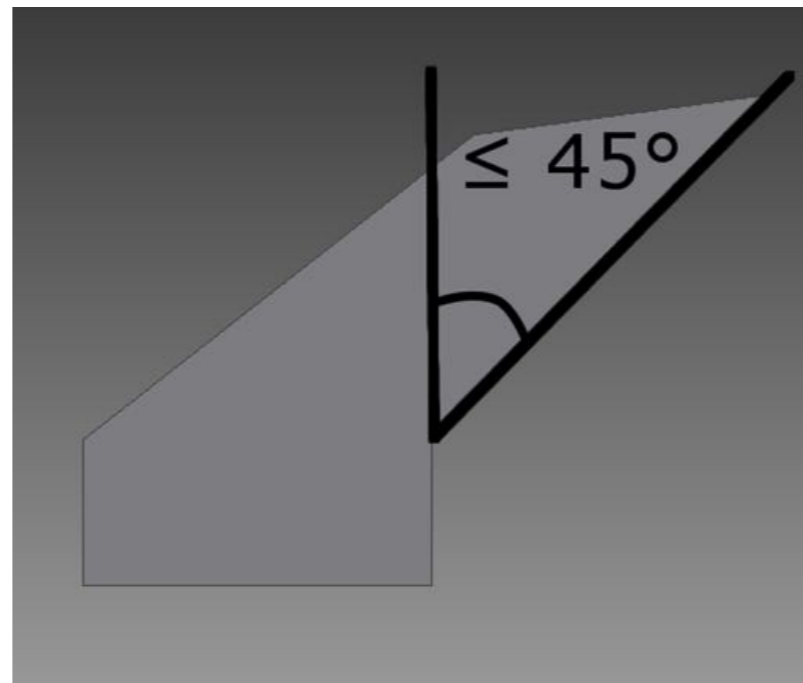
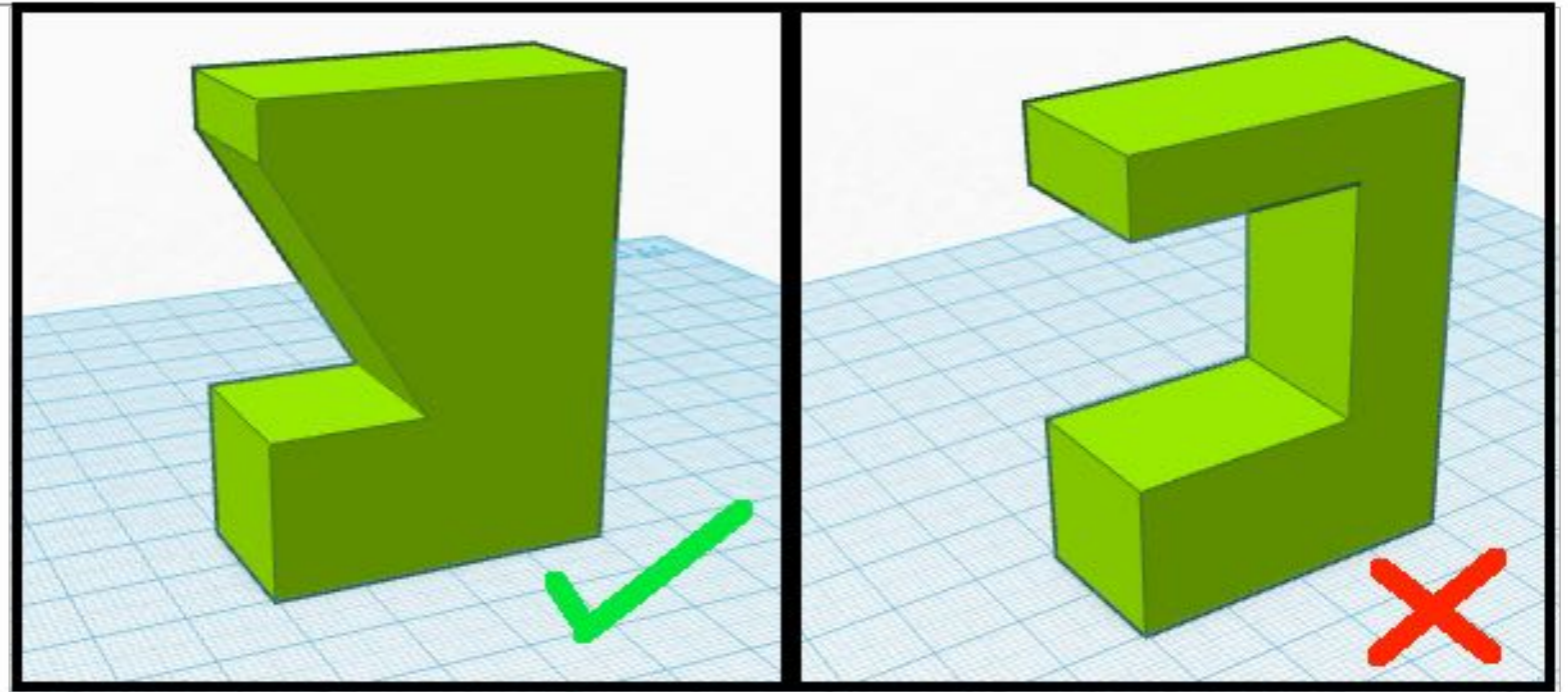
Problems you can solve by modifying the original 3D model (or simply its orientation) or by correcting the mesh



# Attenzione alle sporgenze!



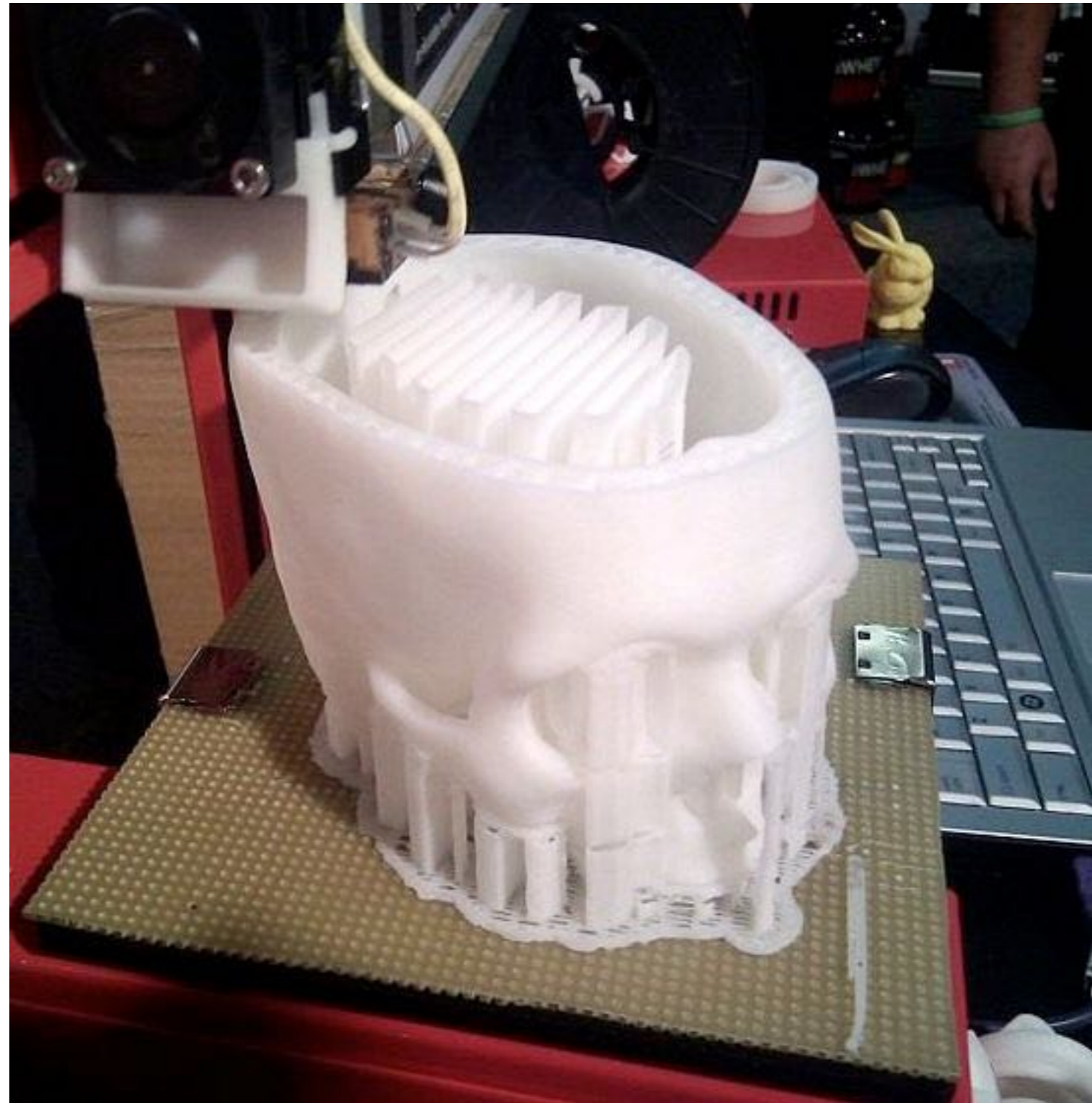
- Le stampanti 3D di solito gestiscono bene le sporgenze fino ai 45 gradi senza trucchi speciali.
- Se possibile, ruotate il modello 3D per minimizzare le parti con sporgenze (prima dello slicing).
- Raffreddate con una ventola la parte durante la stampa, per indurire il filamento appena esce dalla testina (prima che riesca a colare e rovinare la stampa).
- Solo se necessario attivate l'uso del supporto nel software di slicing, nonostante sia utile utilizza più plastica, la stampa richiede più tempo, e dovrete poi rimuovere la plastica di supporto con una lama.



# Support me, please!

---

- Le stampanti con tecnologia FDM normalmente non possono produrre strutture a stalattite o sporgenze estreme, poiché queste non sarebbero supportate durante la stampa. Se non si possono evitare, una sottile struttura di **supporto** può essere aggiunta all'oggetto, essa sarà poi staccata o tagliata via al termine della stampa.
- Quasi tutti i programmi di slicing sono in grado di generare automaticamente queste strutture di supporto.





**CLEANING PROCESS**



**BEFORE**



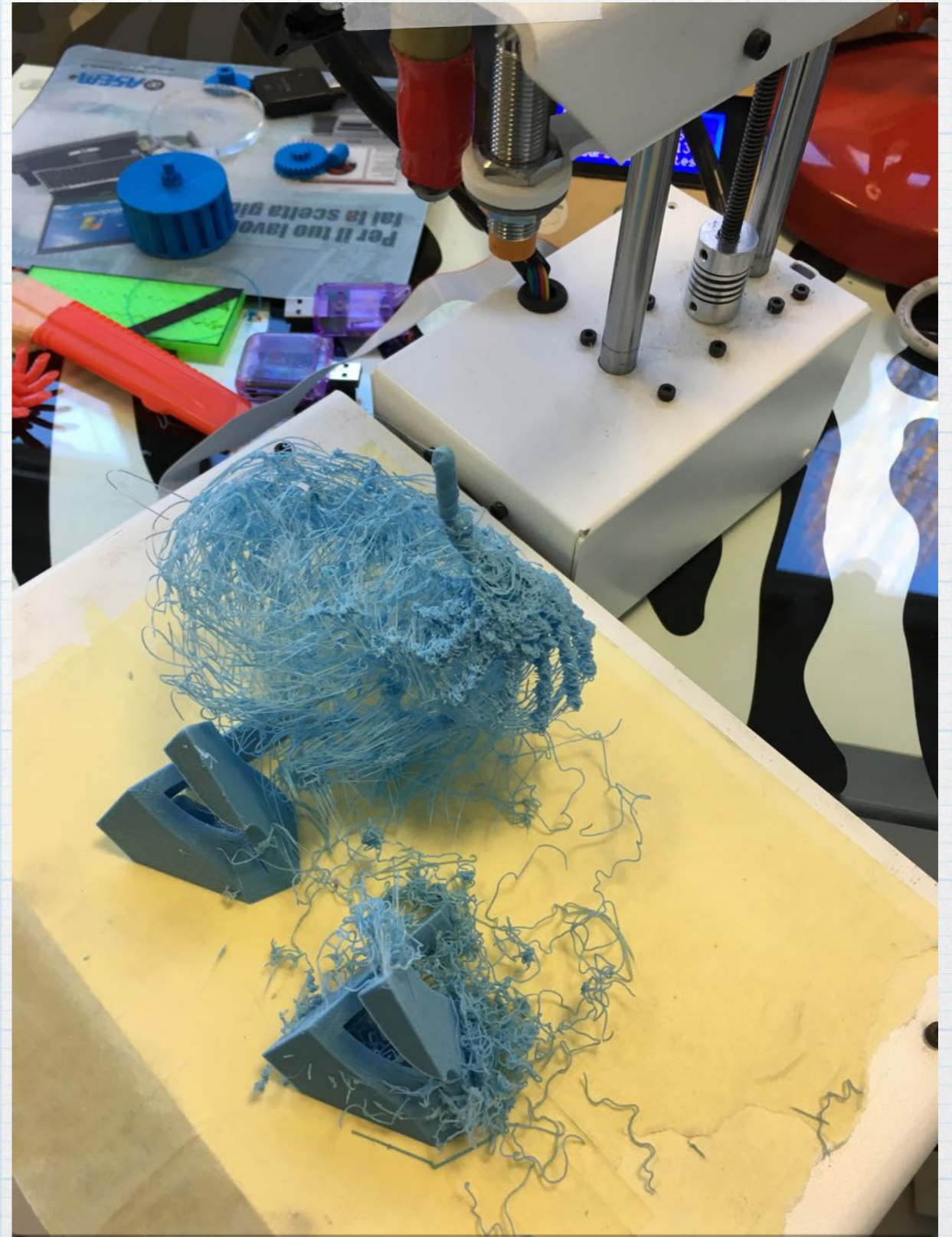
**CLEANING PROCESS**

**AFTER**



# Technical issues

Problems you can solve with a better printer and/or by tuning the slicing parameters





# Delaminazione



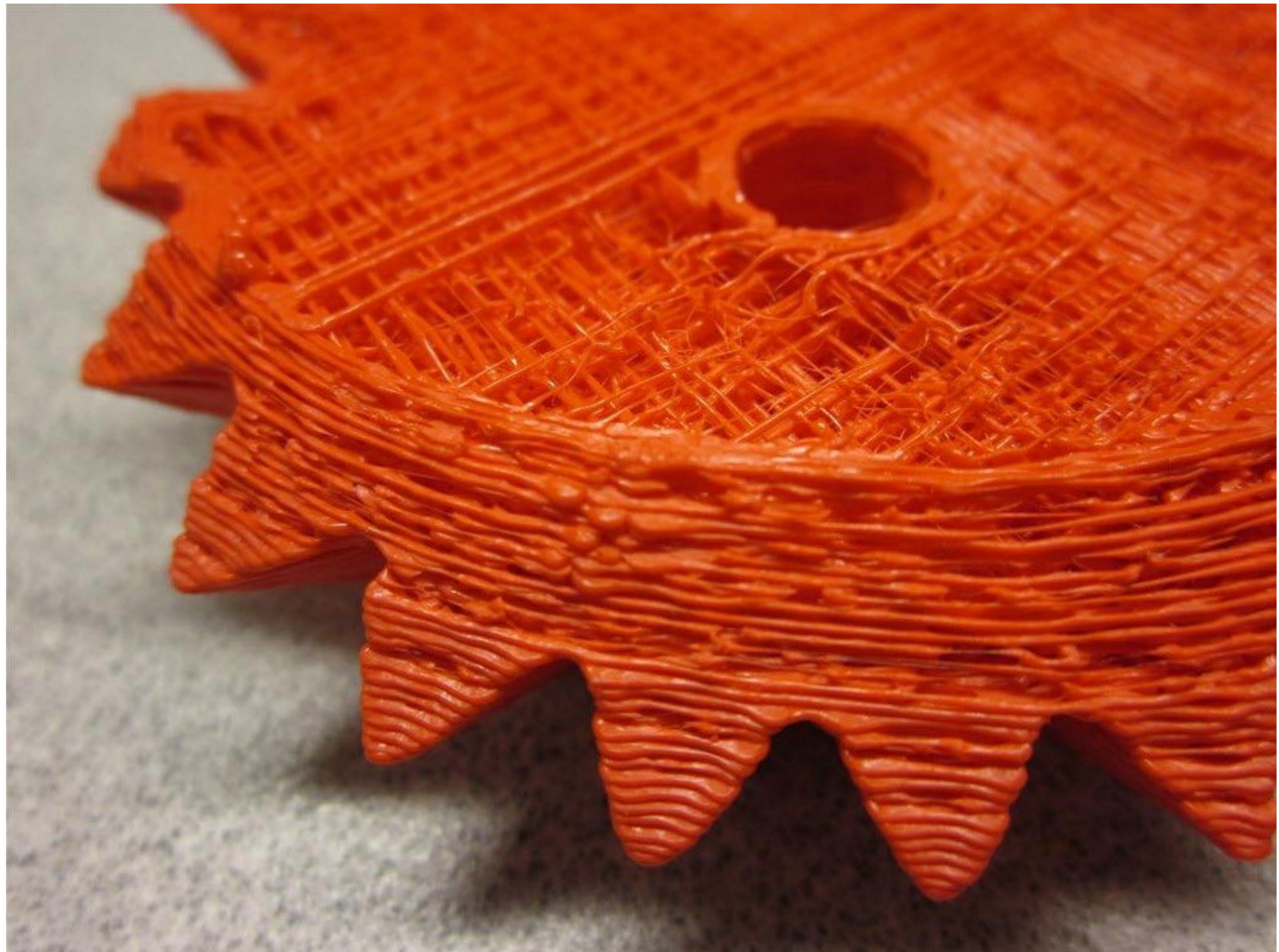
ABS e Nylon in ambiente freddo

# Strings

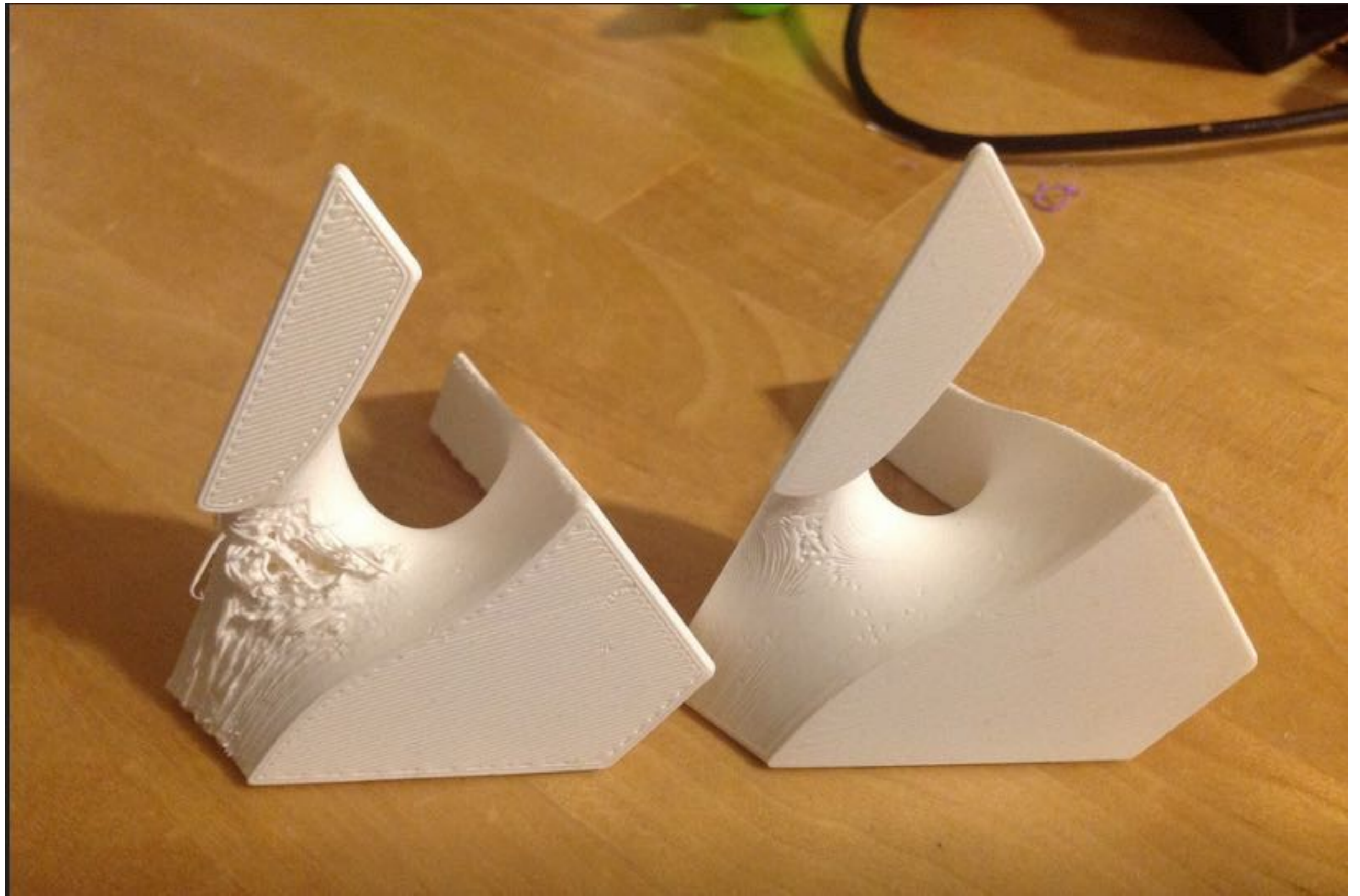
poca ritrazione  
del filamento  
temp troppo alta



flusso di plastica irregolare



Temp o ingranaggio di estrusione sporco



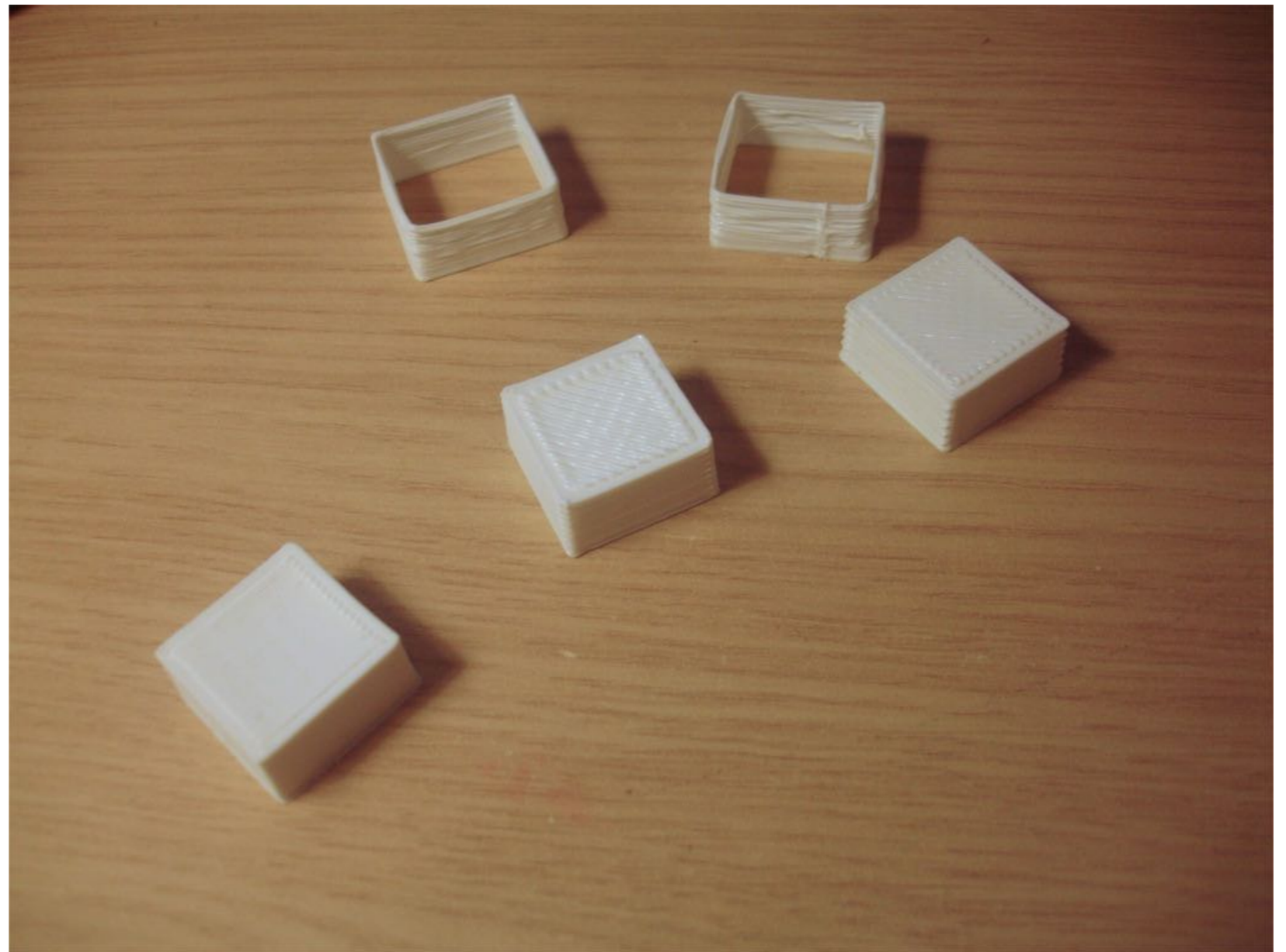
200°

220°

# Pezzi deformati

calibrazione

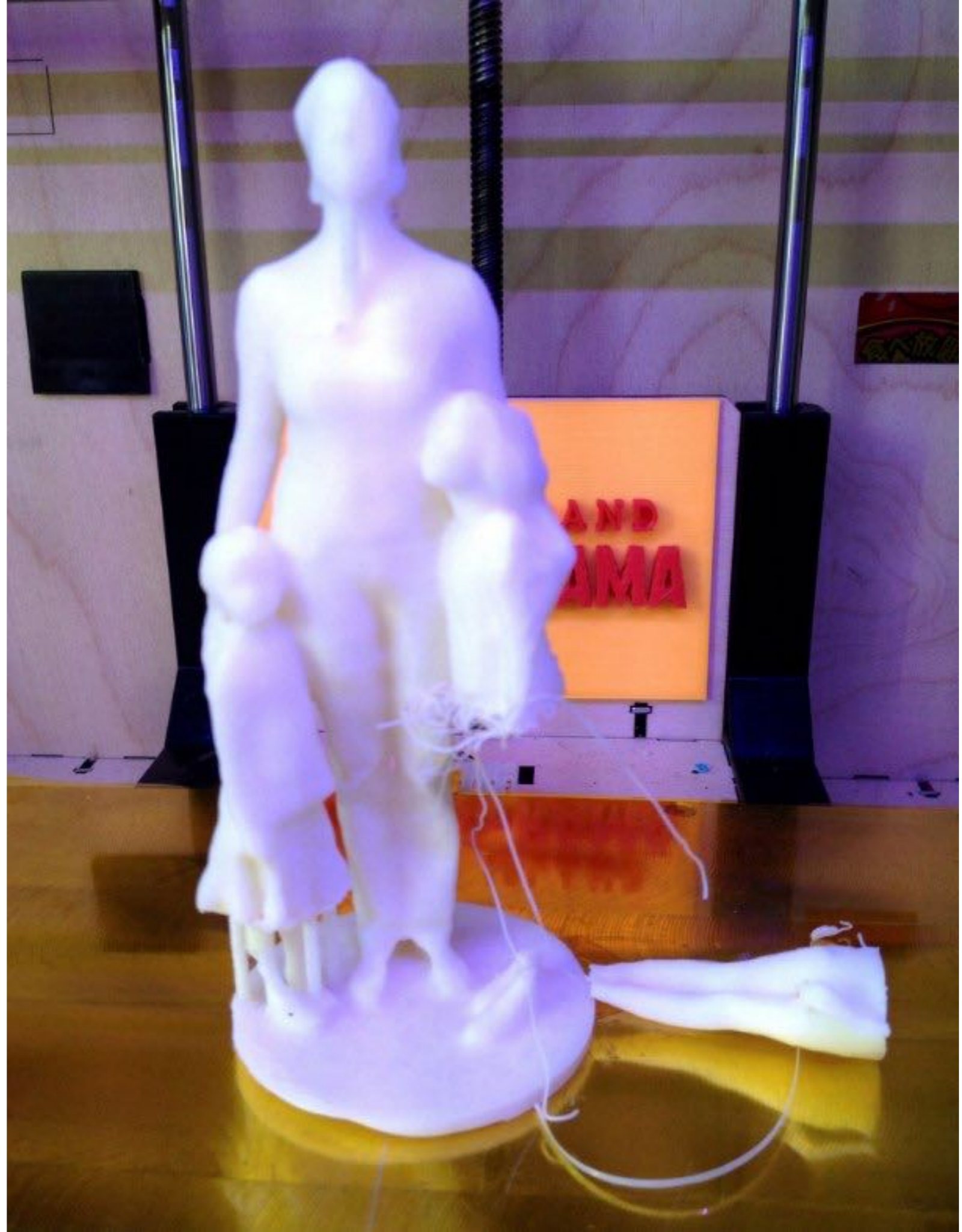
warping



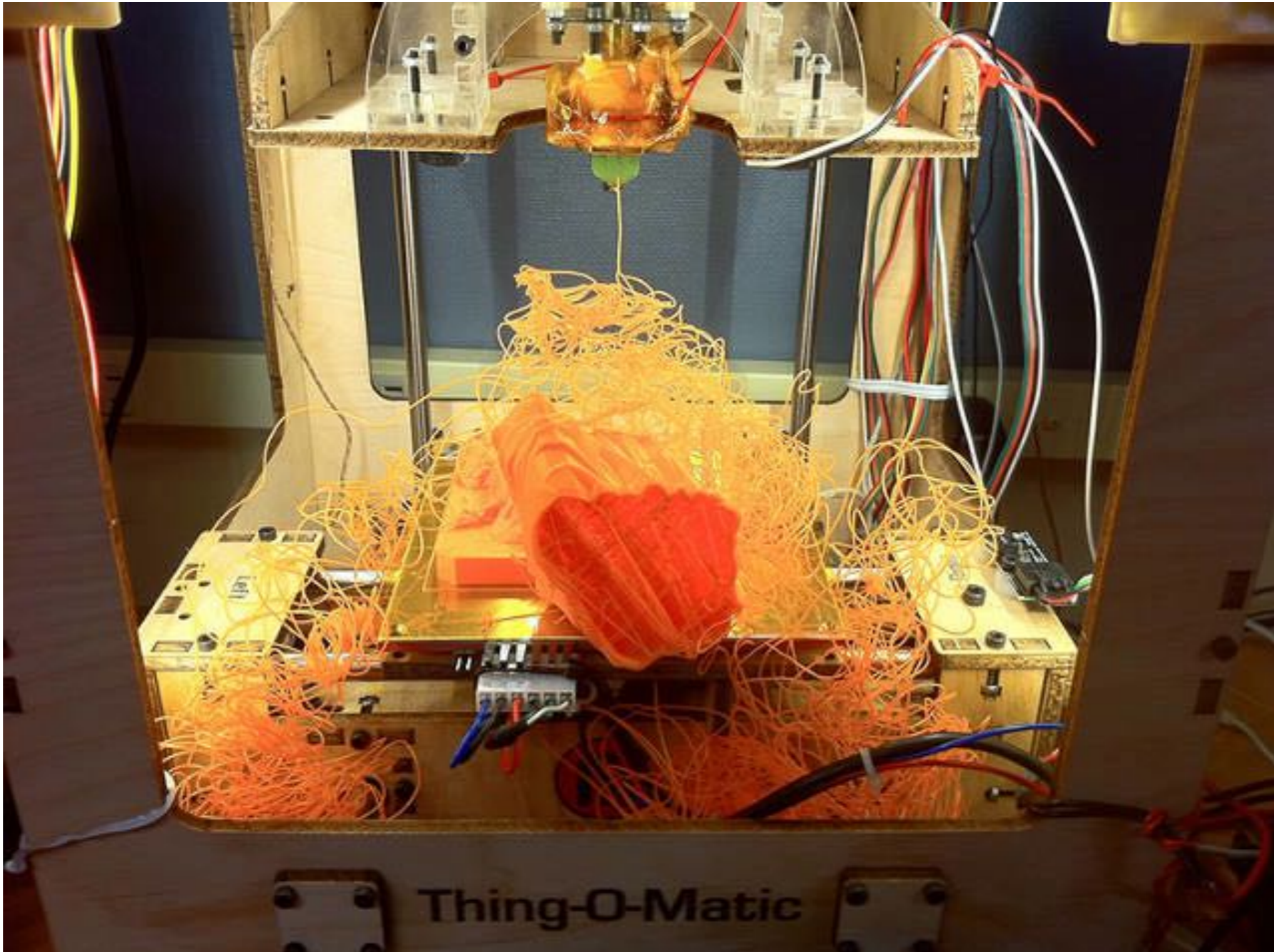
Cinghie che slittano!



dettagli troppo  
sottili

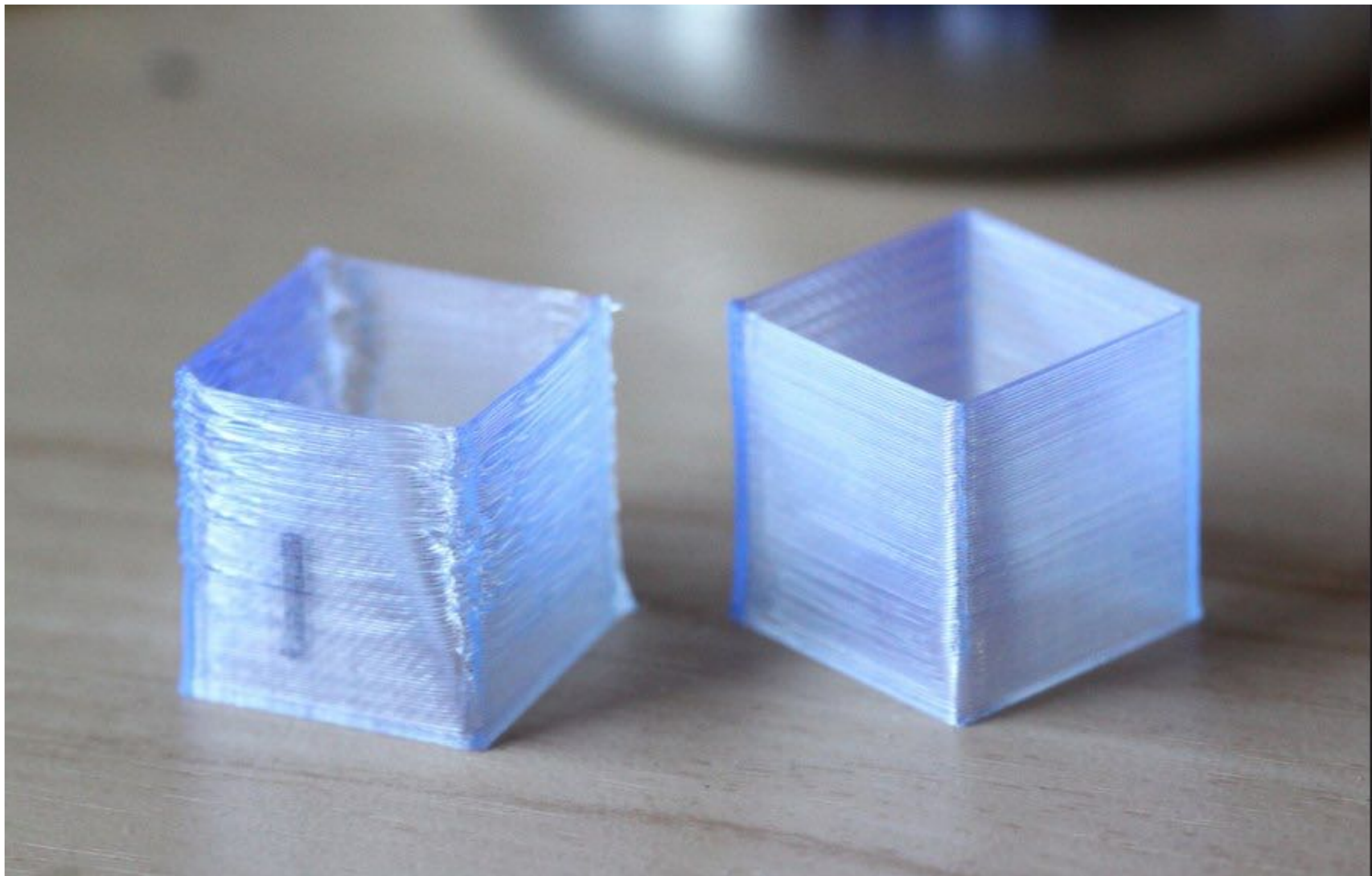


Il pezzo non ha aderito al piano

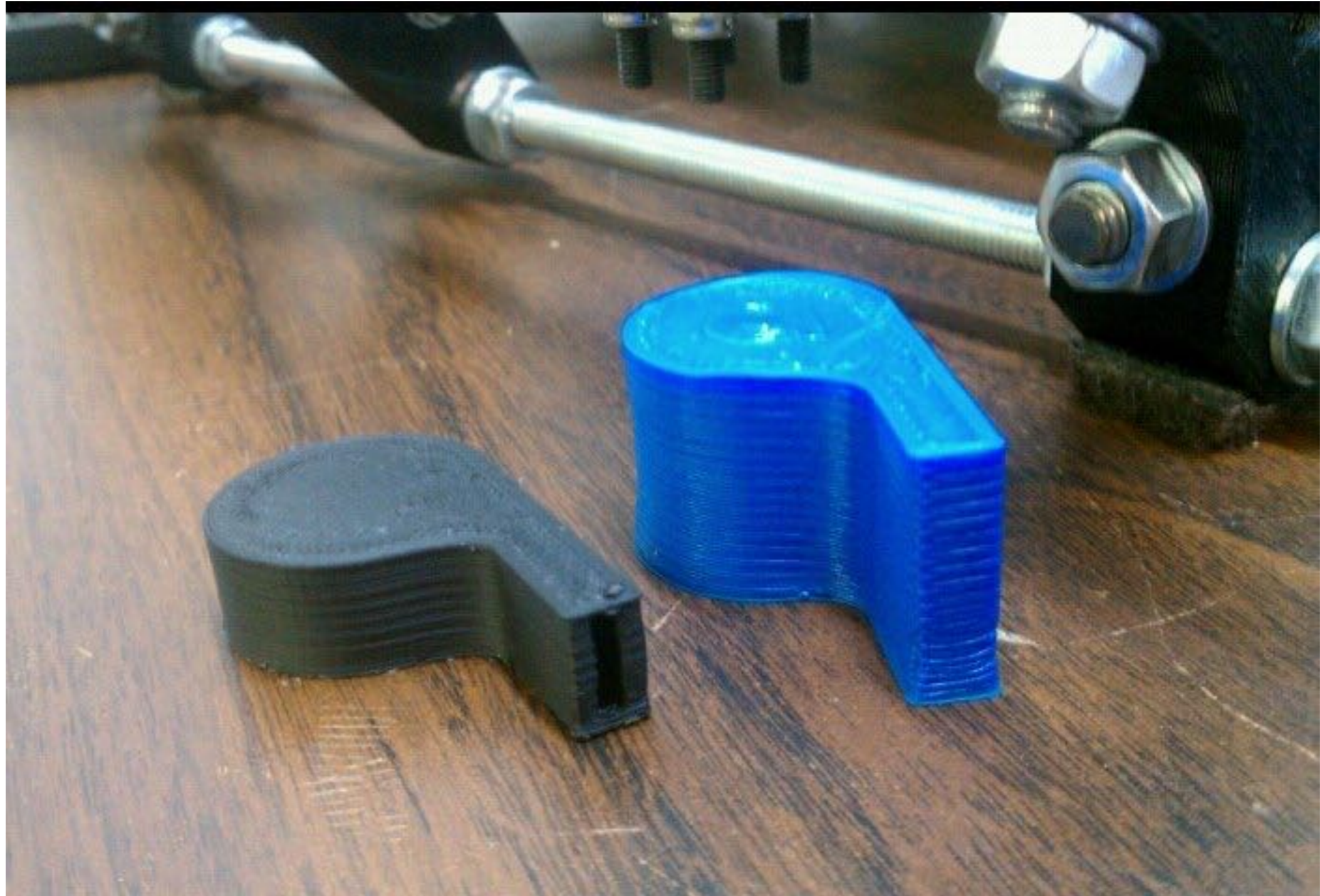


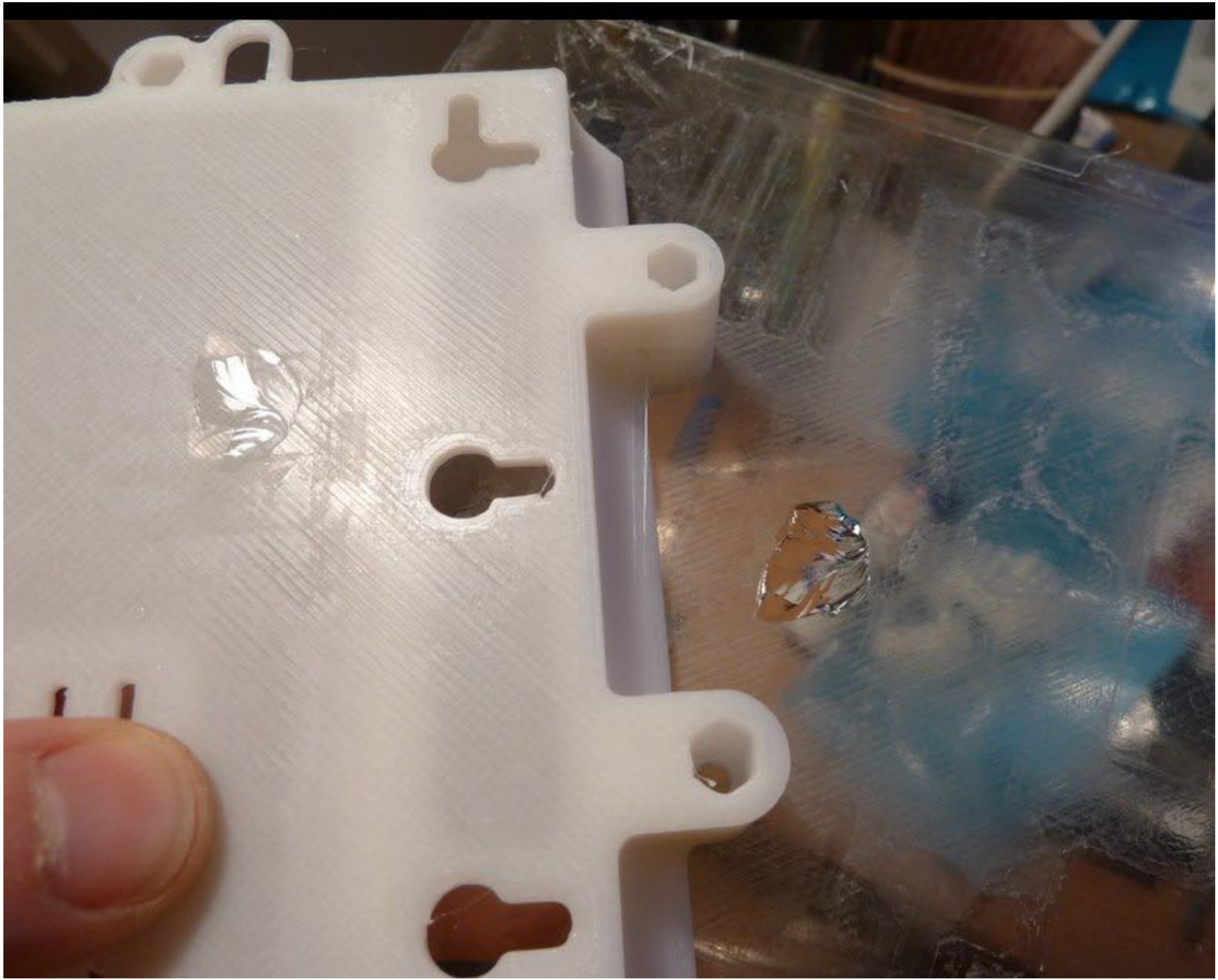


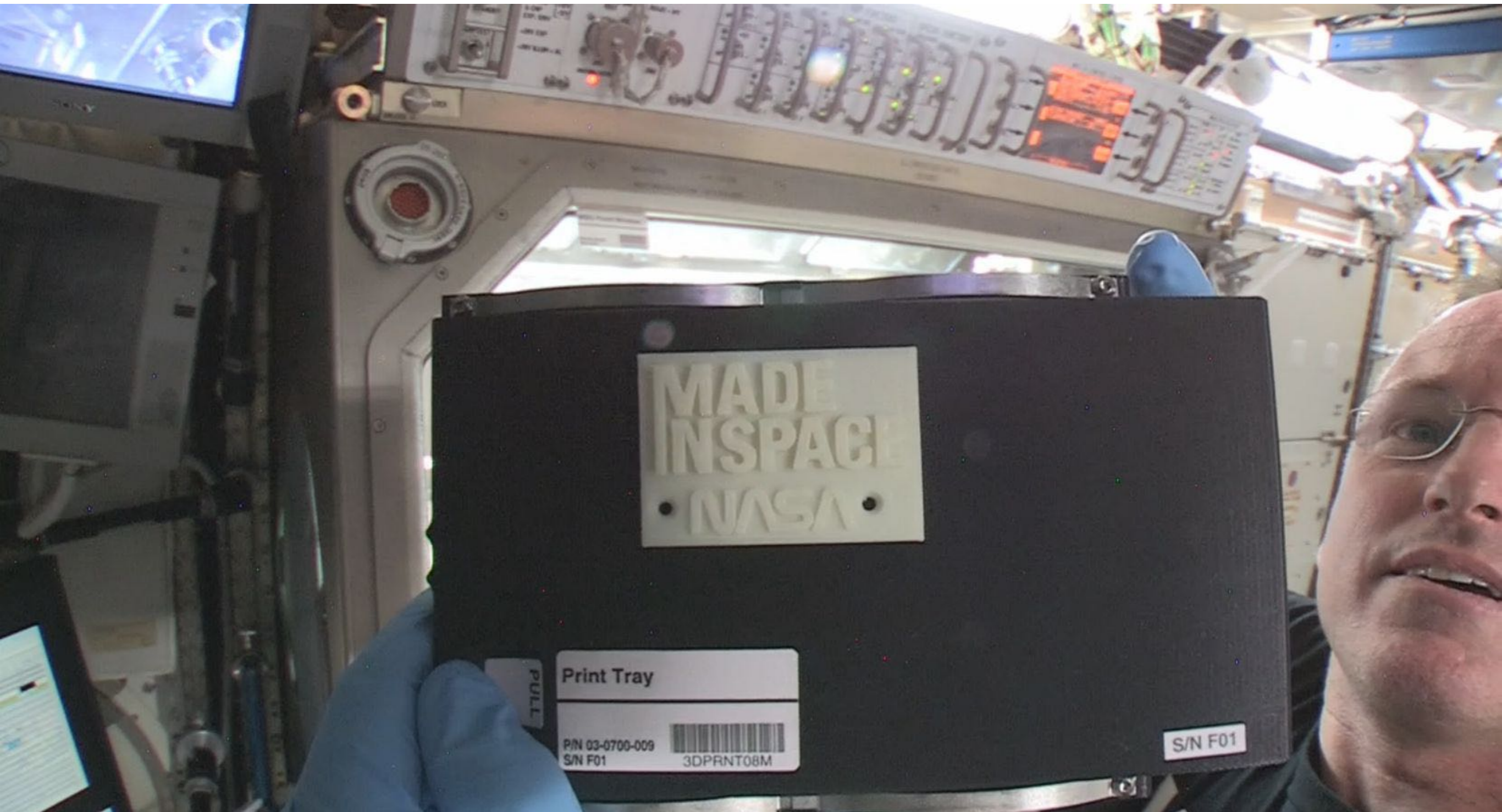
poco raffreddamento



# Errori nello slicing: pieni e vuoti







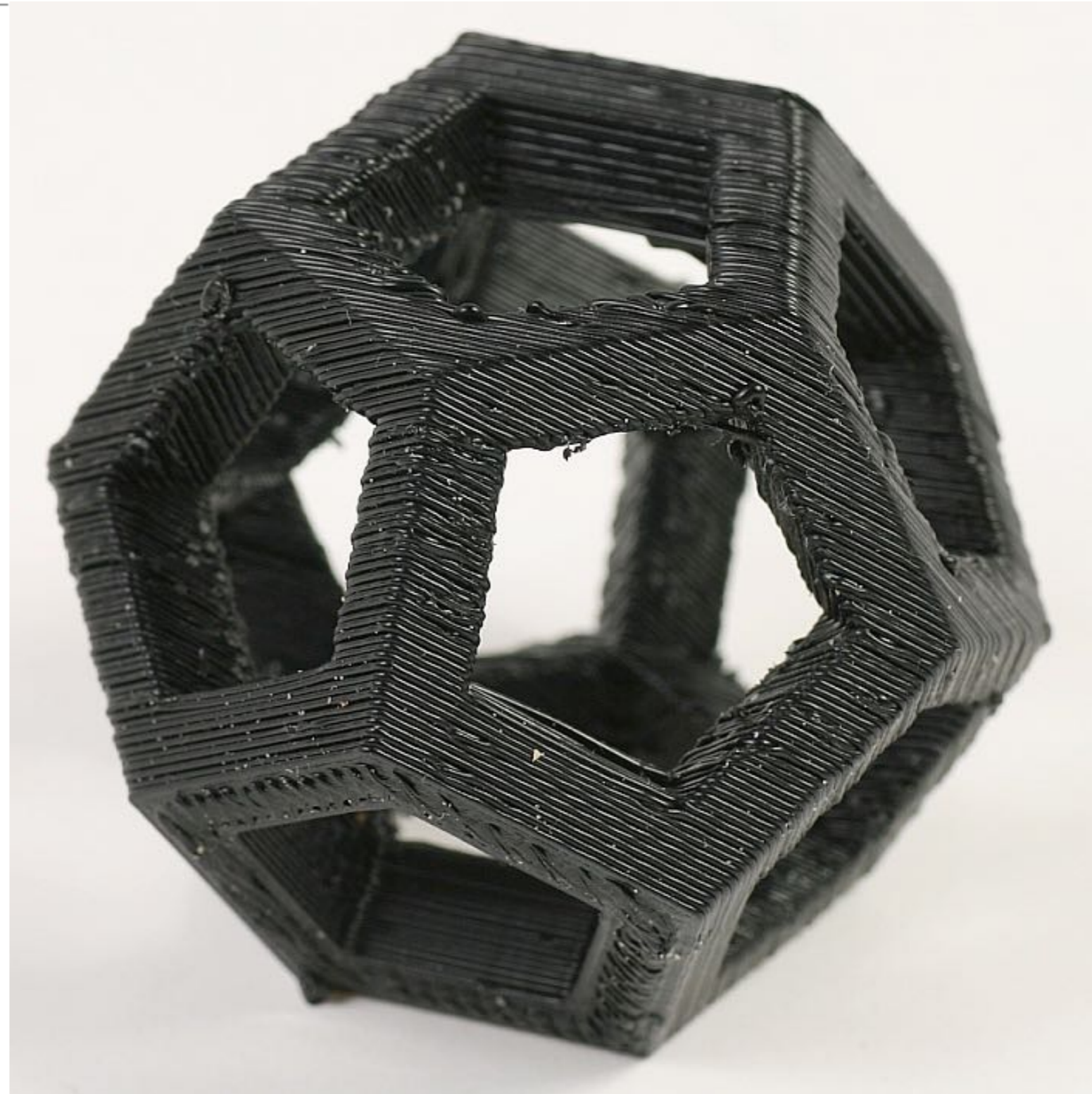
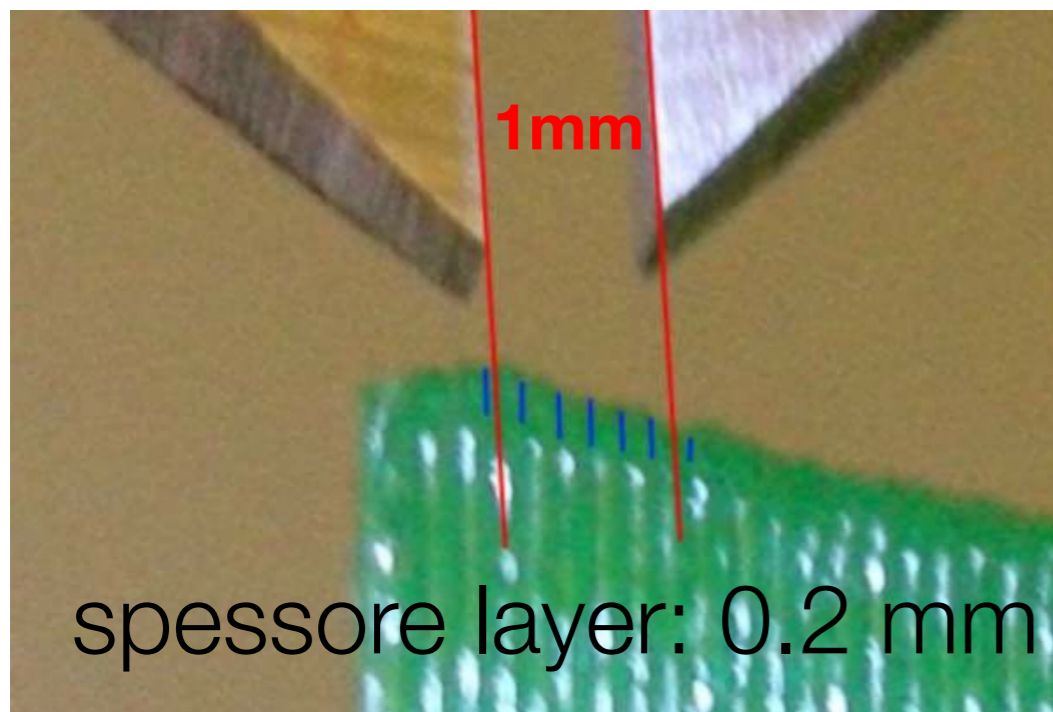


Slicing parameters

(Science or Art?)

# I dettagli che fanno la differenza...

- È difficile stampare dettagli molto piccoli: il diametro del foro dell'ugello è di 0.3–0.5 mm, la risoluzione del movimento della testina/piattaforma è di ~0.1 mm.
- Lo spessore tipico di uno strato (layer) è di 0.2 mm (0.05 – 0.5 mm).



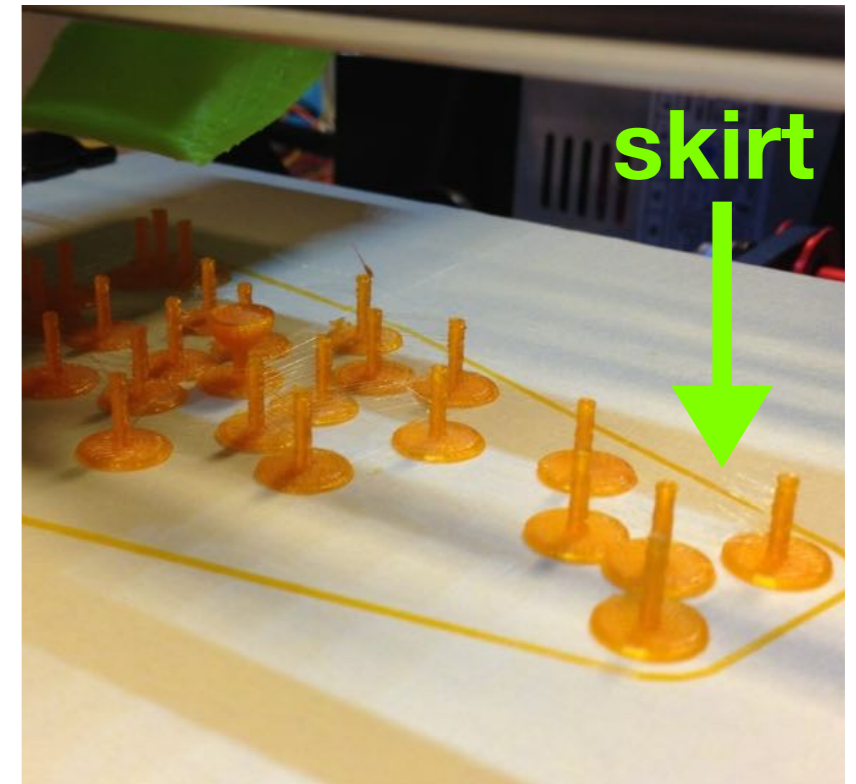
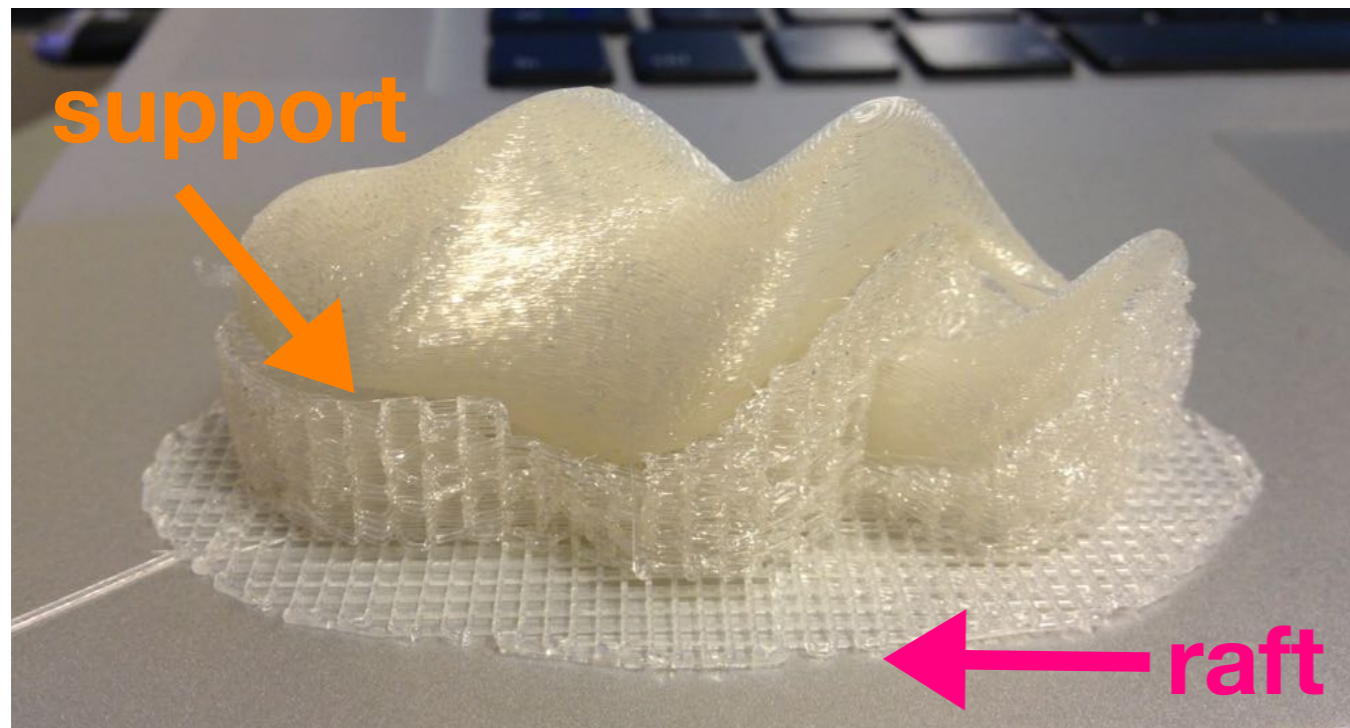
# Layer height



0.1mm 0.2mm 0.3mm 0.4mm

# “Raft” e “Skirt”

- La stampa di un oggetto può avvenire su uno strato di “raft” che poi verrà eliminato (è fatto della stessa plastica di stampa e supporto) piuttosto che direttamente sulla piattaforma di stampa. Il raft ha una impronta più larga dell’oggetto che quindi *aderisce meglio*. Può anche essere usato per prevenire *distorsioni*.



- A volte, all’inizio della stampa il filamento esce a malapena dall’ugello ancor vuoto. Per risolvere questo problema, un po’ di plastica extra, detta **skirt**, viene estrusa *attorno all’oggetto* prima della stampa.



# Riempire il vuoto

- La stampa 3D è un processo additivo. Ciò significa che non pagate perché una macchina rimuova del materiale, bensì per costruire depositandolo. Perciò meno materiale è richiesto dal vostro modello (cioè minore è il volume), minore è il costo e più sono veloci i tempi di stampa.
- Per questa ragione, la maggioranza degli oggetti è stampata con il parametro di riempimento (*infill*) nell'intervallo dal 10% al 50%.
- Si può ottenere una maggior robustezza con un giusto numero di *perimetri* (shells), e di *bottom/top layers*.



# INFILL PERCENTAGE

The variable that defines the density of the internal support structure of FFF printed objects  
Rule-of-thumb: the higher the percentage of infill, the denser the object



0%



5%



10%



15%



100%



75%



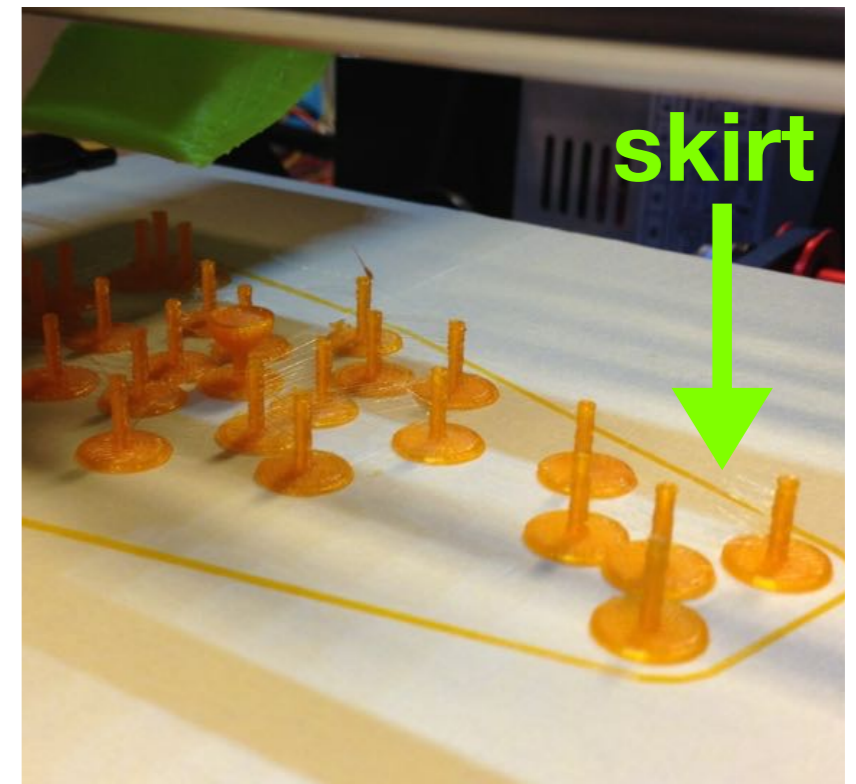
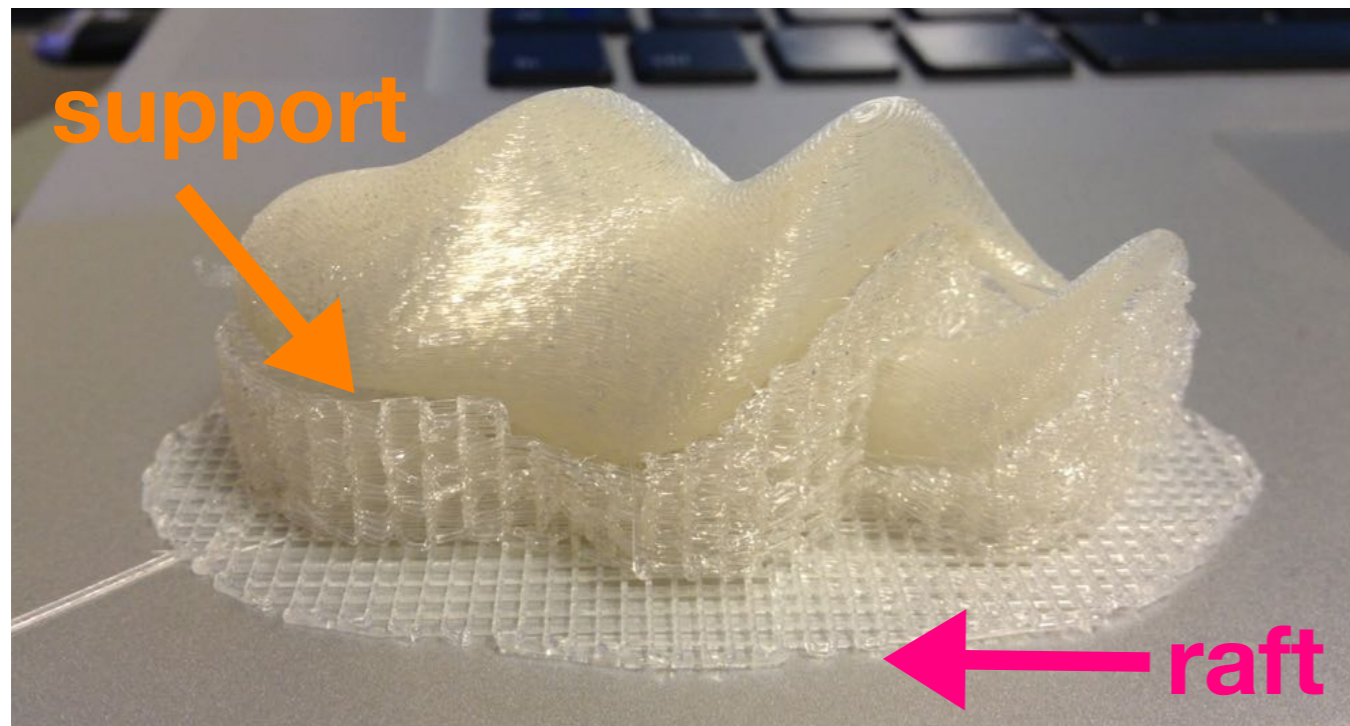
50%



25%

# “Raft” e “Skirt”

- La stampa di un oggetto può avvenire su uno strato di “raft” che poi verrà eliminato (è fatto della stessa plastica di stampa e supporto) piuttosto che direttamente sulla piattaforma di stampa. Il raft ha una impronta più larga dell’oggetto che quindi *aderisce meglio*. Può anche essere usato per prevenire *distorsioni*.

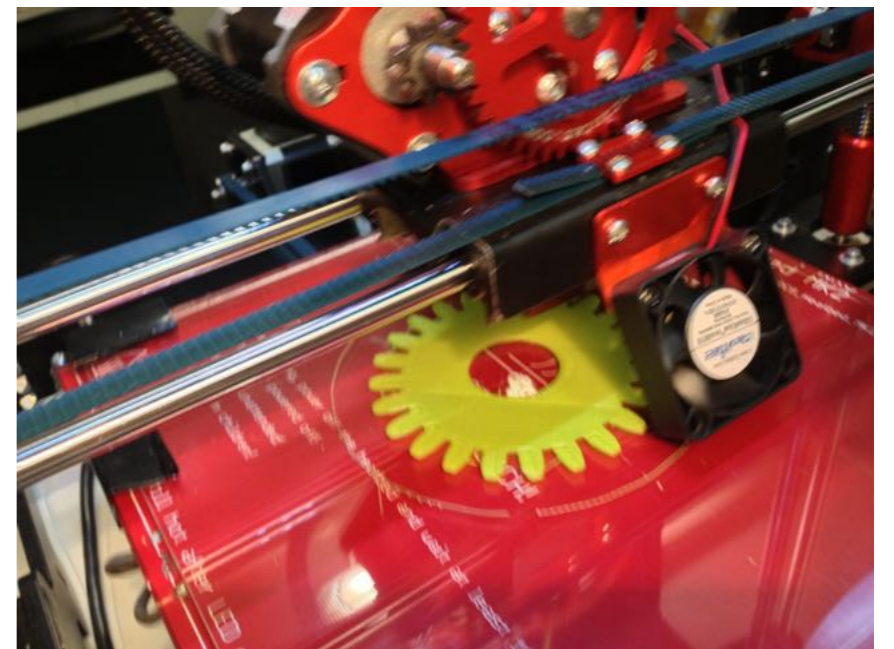
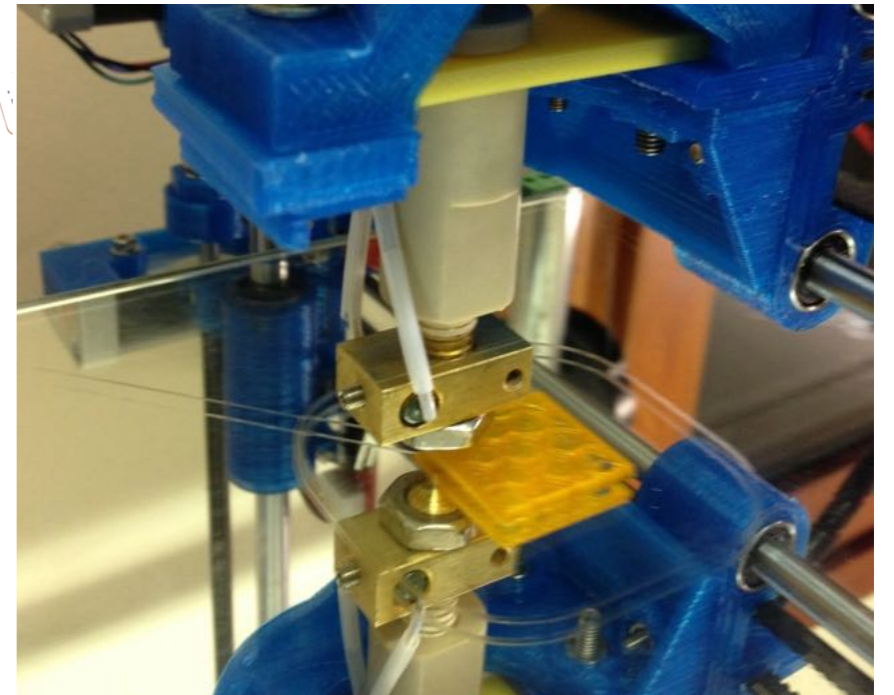
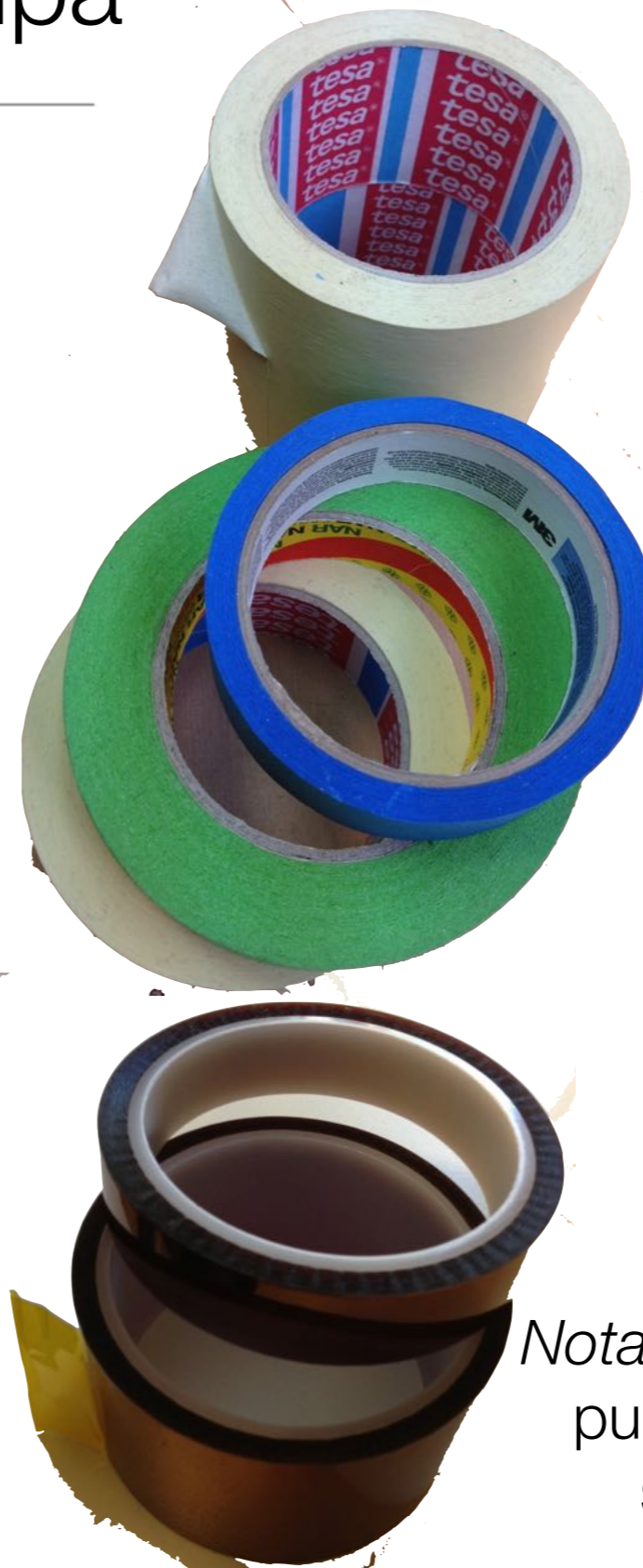


- A volte, all’inizio della stampa il filamento esce a malapena dall’ugello ancor vuoto. Per risolvere questo problema, un po’ di plastica extra, detta **skirt**, viene estrusa *attorno all’oggetto* prima della stampa.

# Piattaforma di stampa

---

- Lo scopo è far sì che **l'oggetto resti attaccato** alla piattaforma. Alcune soluzioni sono:
- nudo vetro (o specchio)
- legno compensato o alluminio
- PLA: vetro/compensato/alluminio coperti da uno strato di **nastro carta**
- ABS: stessa base, ricoperta da nastro **Kapton** e **riscaldato** (~100+ °C)
- usare della colla (spray)...

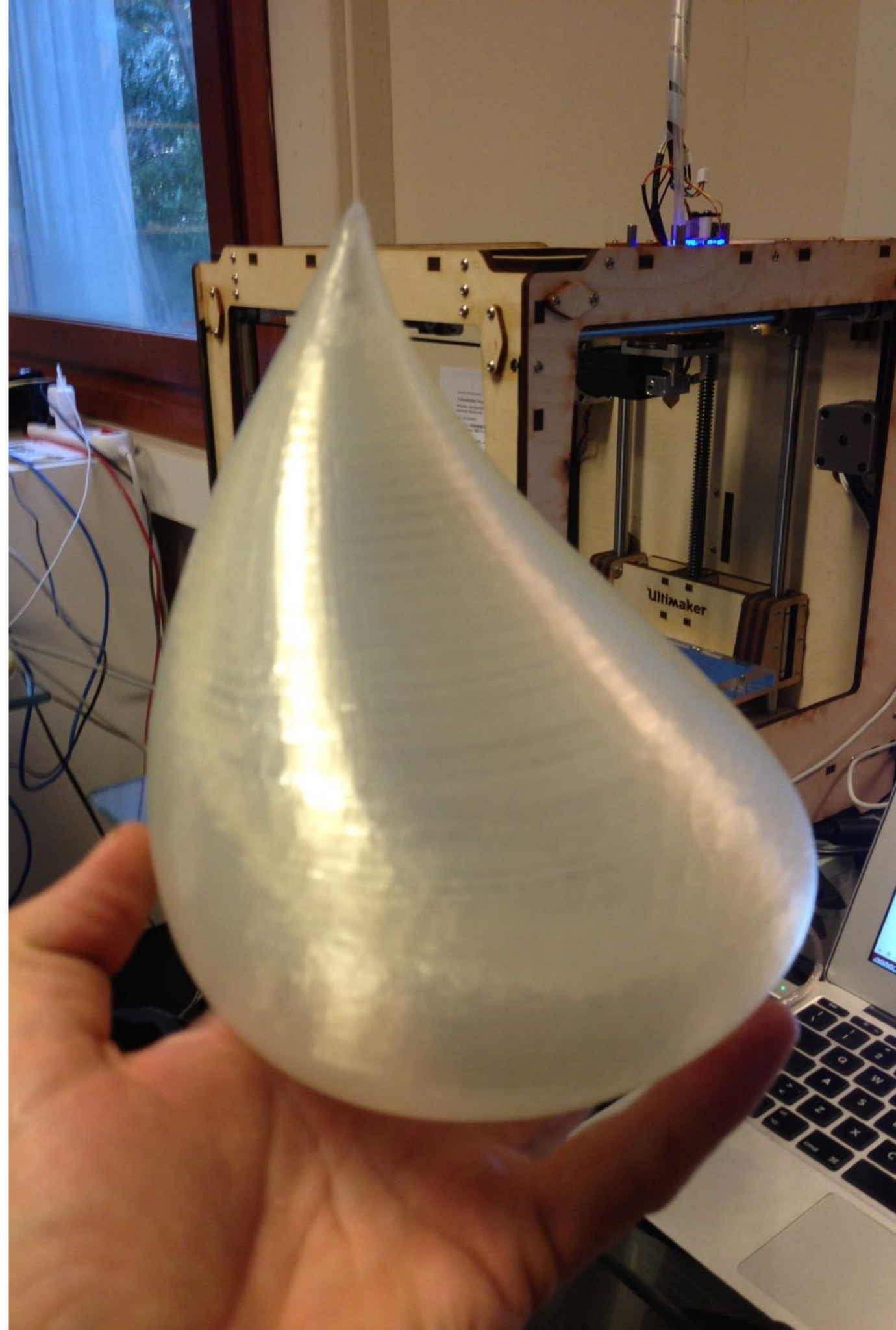


*Nota: una piattaforma non riscaldata può stampare ABS solo se viene spruzzata con lacca/colla...*

# Post-processing and finishing

---

- After the printing process has finished, leave the object on the heatbed for a few minutes to allow to cool down (this will make it easier to remove the object from the platform).



Join multiple prints



# Sand paper



# Polish



BEFORE



AFTER



TREATMENT: REACTING POLYMER

[AIRWOLF3D.COM](http://AIRWOLF3D.COM)



Resine epossidiche bi-componente

**XTC-3D®**



vapori di acetone



vapori di Acetato di Etile



<http://www.printedsolid.com/smoothpla/>

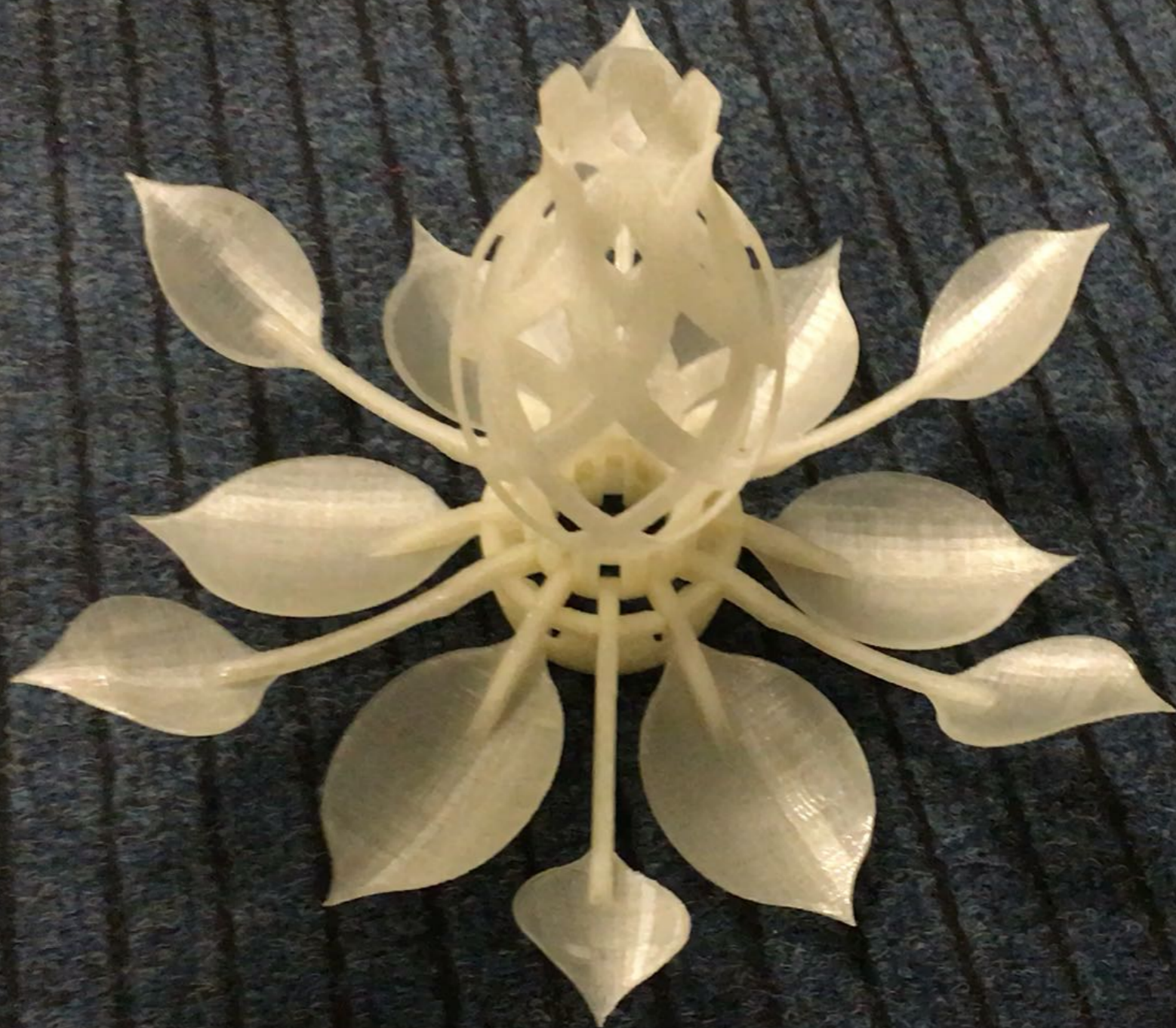


**3D PRINT**

**SMOOTH**

**PRIMER**

**PAINT**

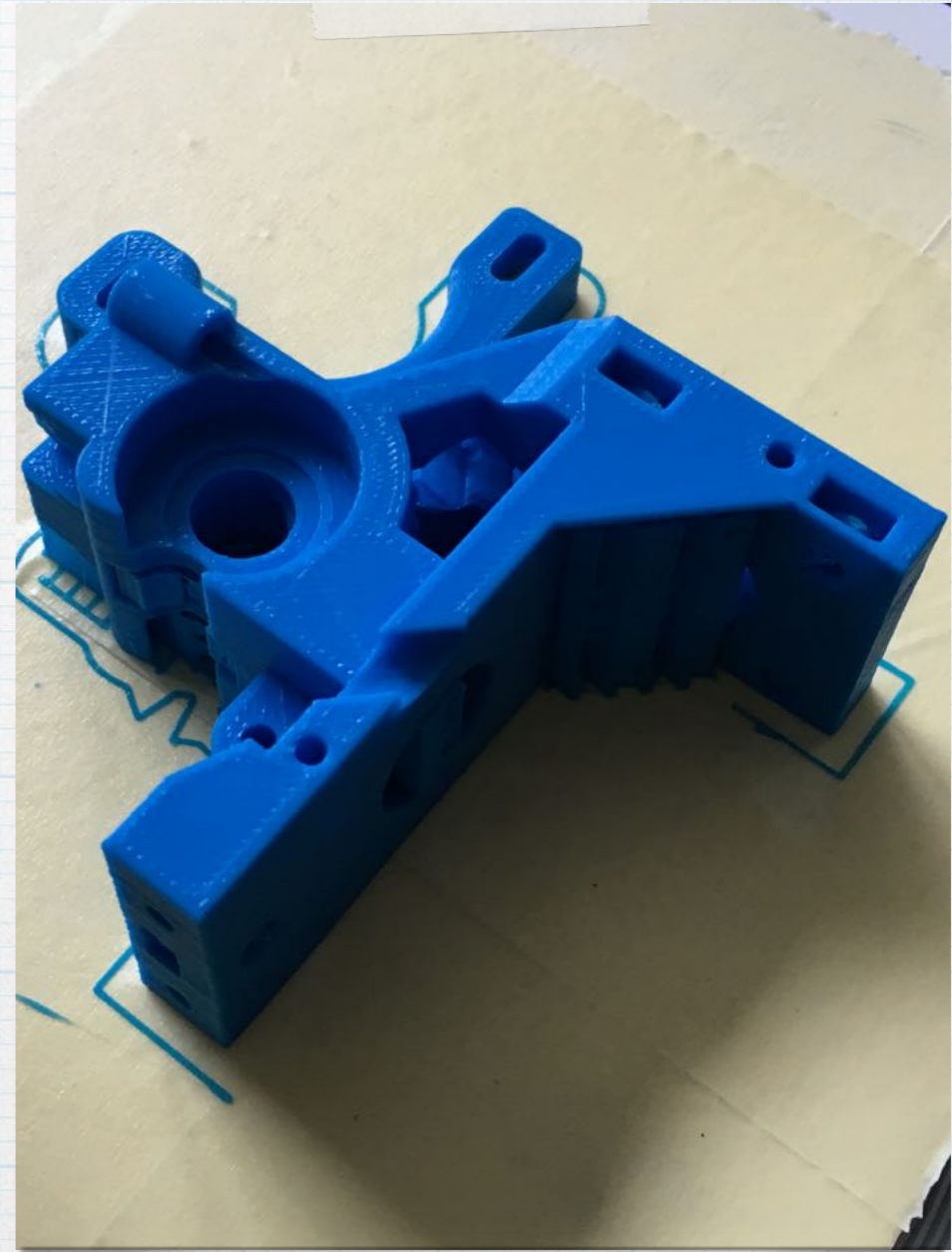


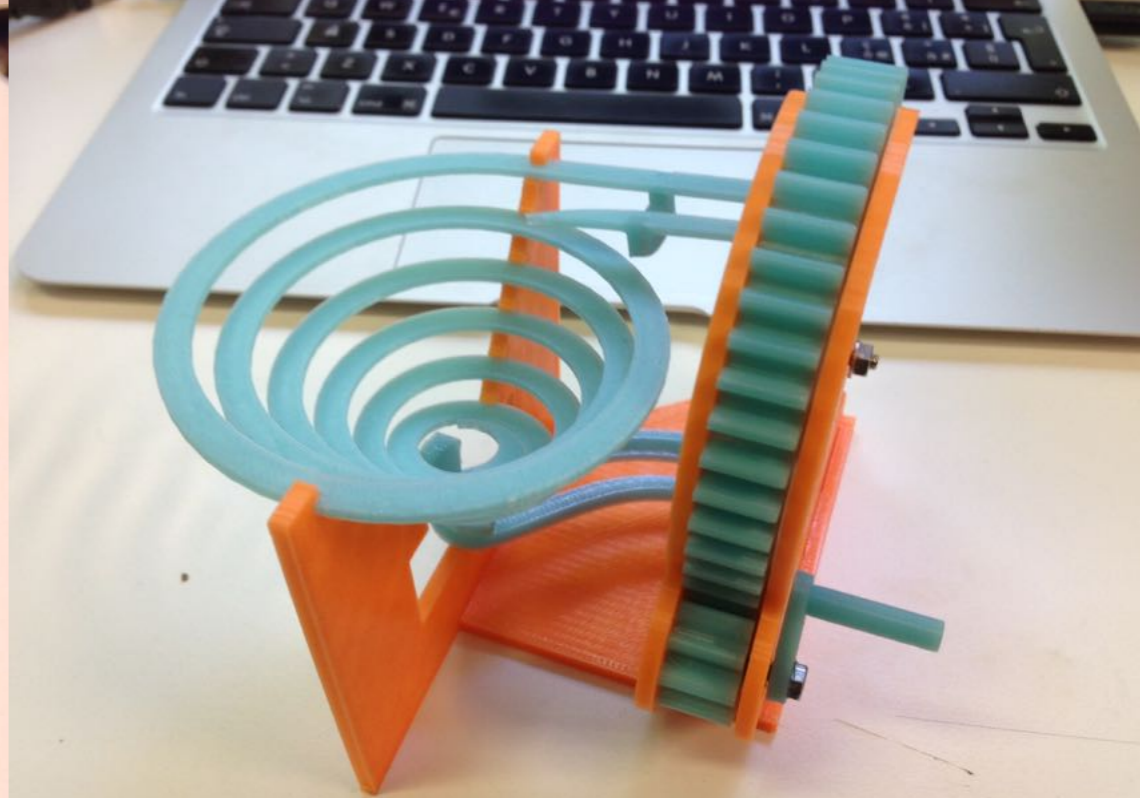
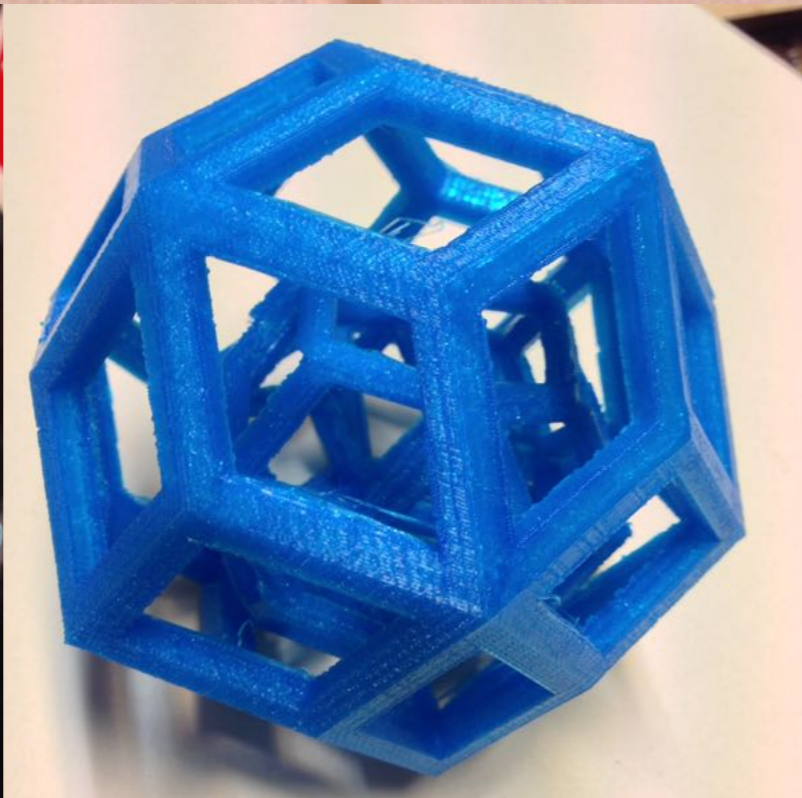
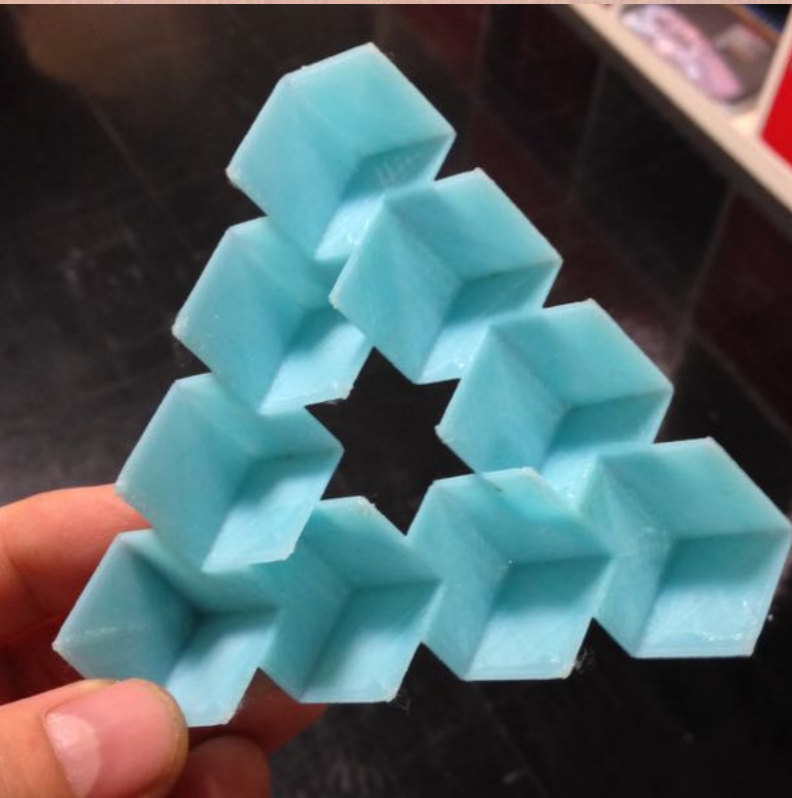
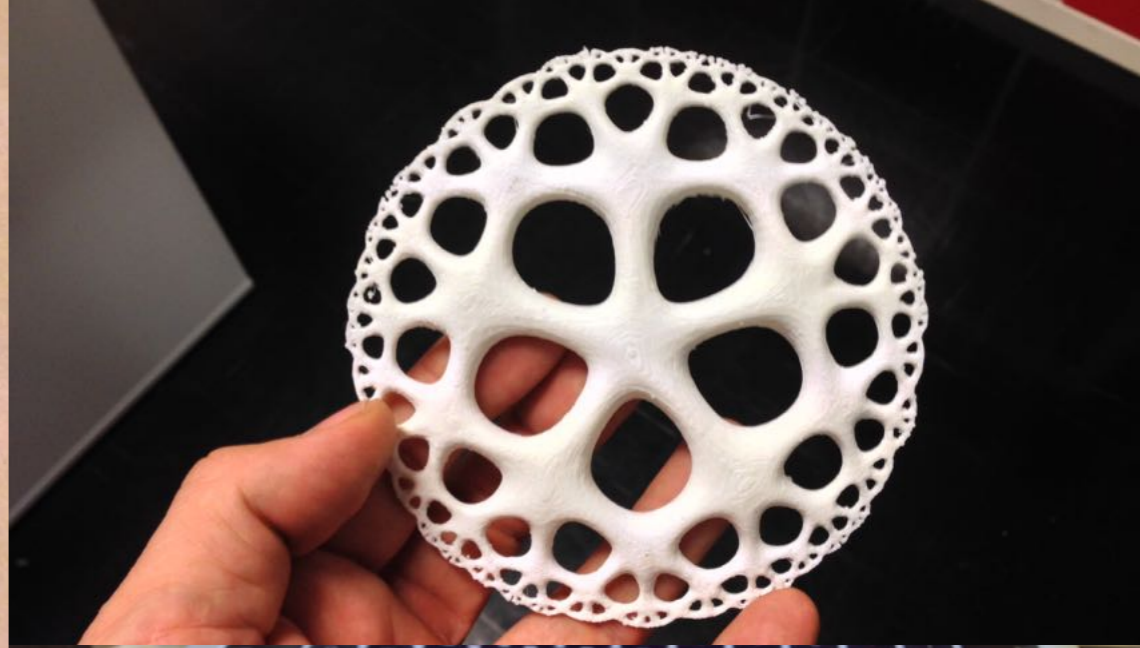
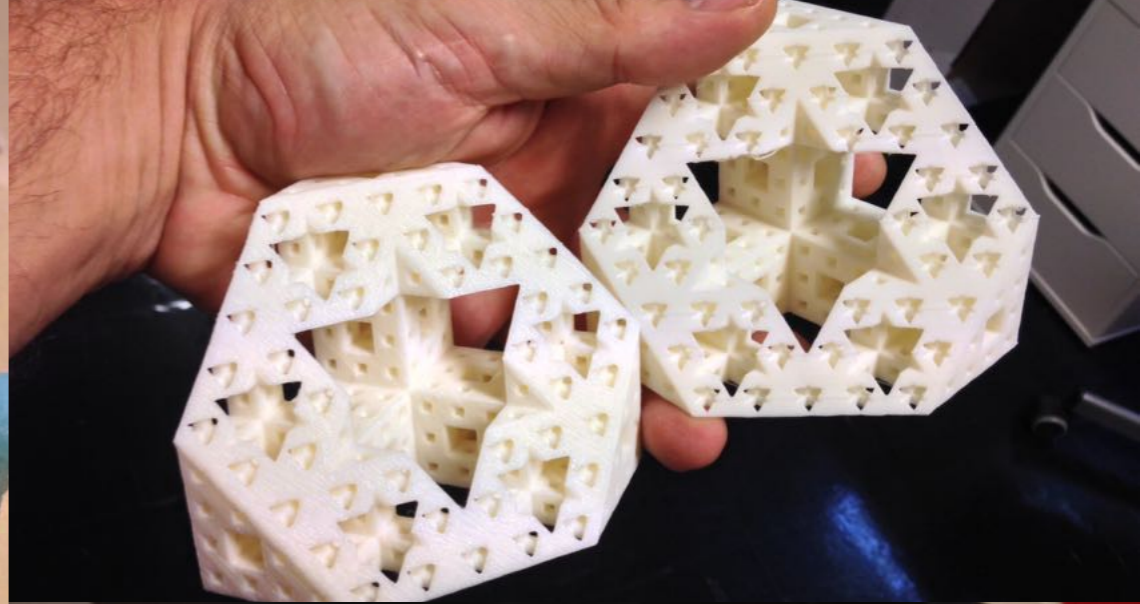
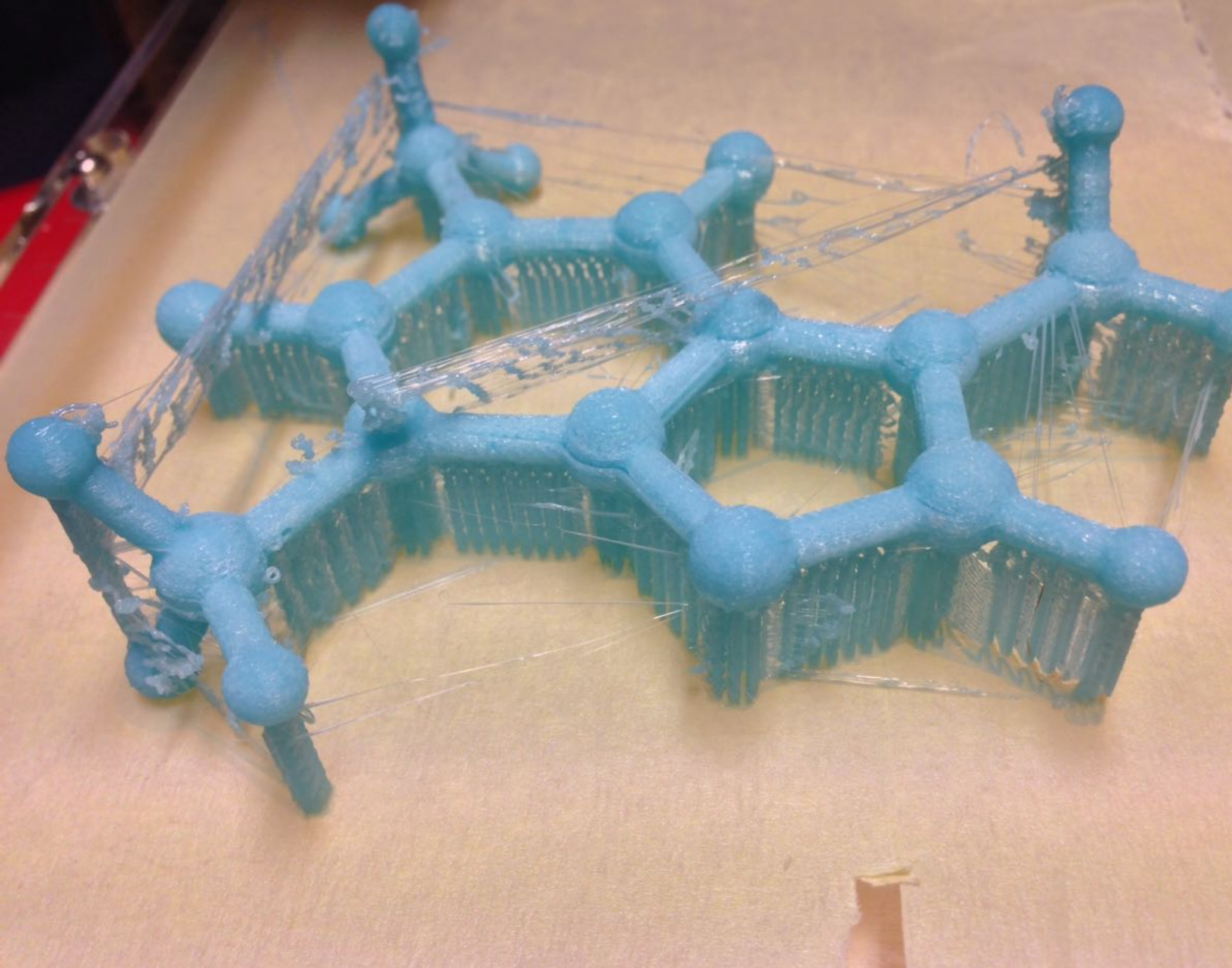
# Modeling for 3DP

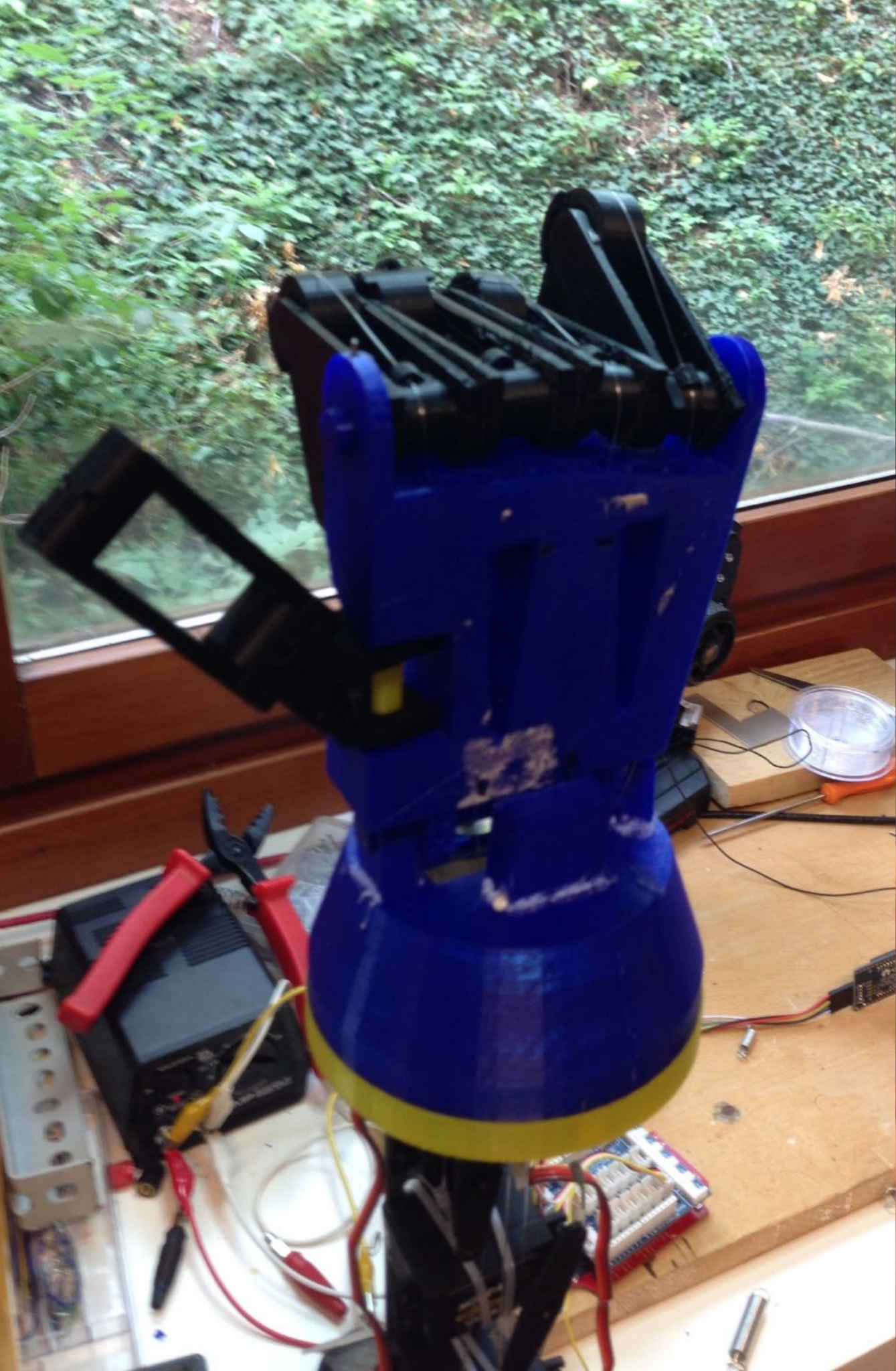
# Something old

## 3DP-oriented modeling

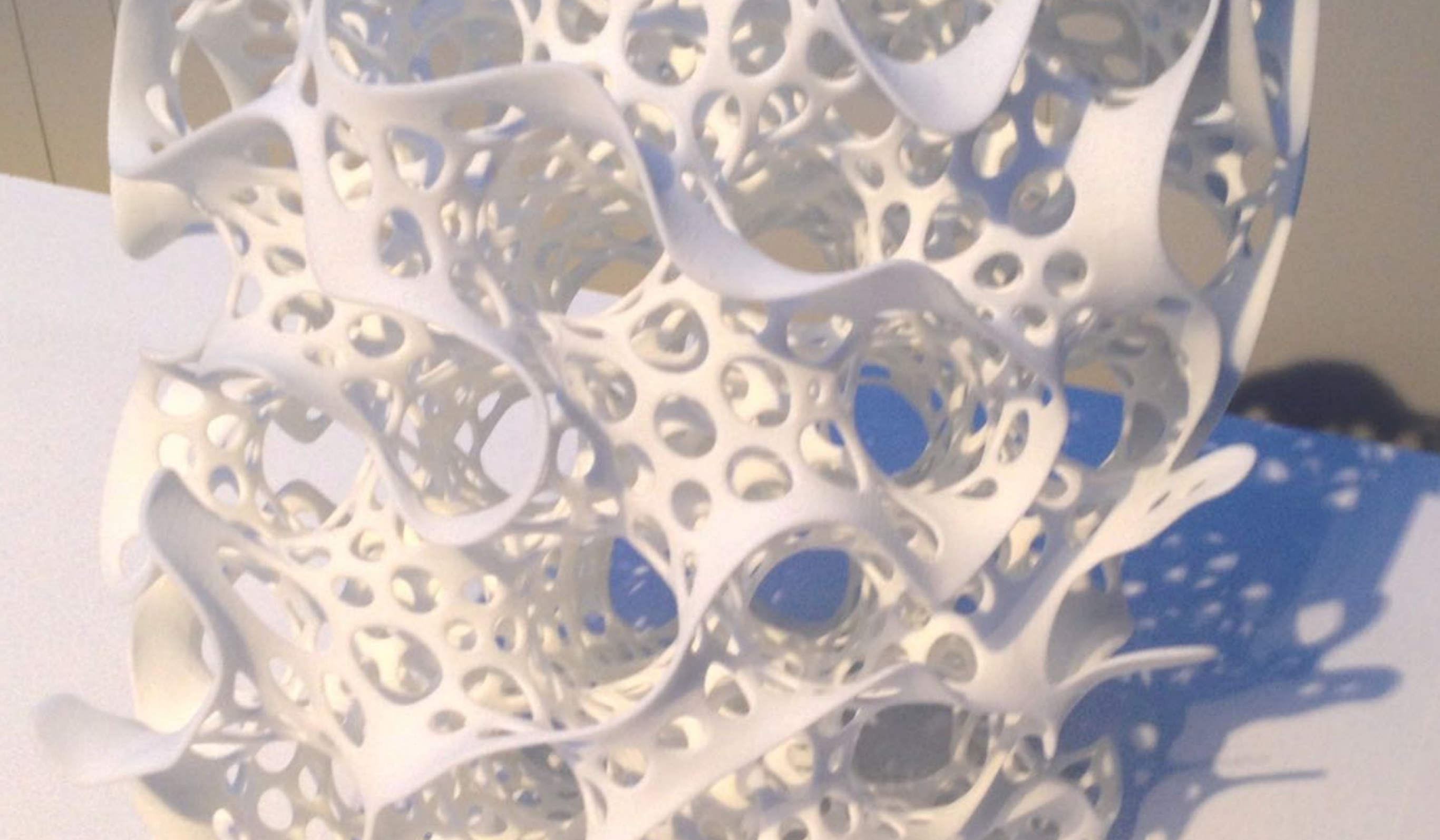
- traditional objects
- optimized for FDM (or other 3DP technologies)
- to avoid/minimize supporting, bridging, ...











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

... we are investigating



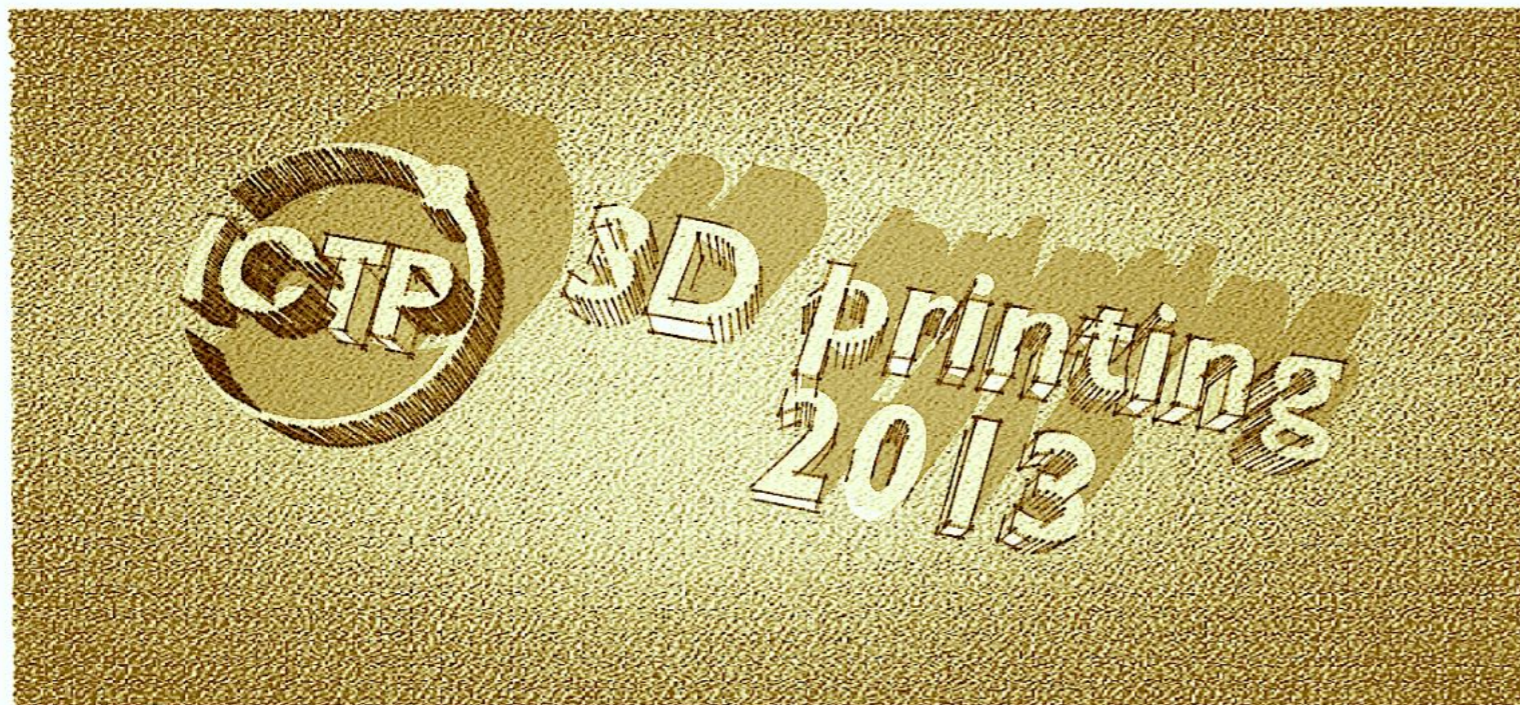
The Abdus Salam  
**International Centre  
for Theoretical Physics**  
www.ictp.it



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.



**DIRECTORS**

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

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

**M. ZENNARO**

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

# An article on Nature

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

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Archive | Volume 487 | Issue 7405 | News Feature | Article

►► 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



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 20-hour noisy but painless delivery of whirring motors and spitting plastic. This modern miracle had endured a lengthy gestation: it took years for Zollikofer's collaborators to find suitable bones from a Neanderthal neonate, 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\$50,000 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 chipped away. These days, personal kits go for as little as \$500, says Terry Wohlers, a consultant and market analyst based in Fort Collins, Colorado — although industrial systems cost an average of \$73,000. Last year, he says, nearly 30,000 printers were sold worldwide, with academic institutions buying one-third of those in the \$15,000–30,000 price range.

Early adopters are 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 conferences, more and more people are carrying printouts of their favourite fossils or bones. "Anyone who thinks of themselves 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 printouts are yielding insights that are not possible with more conventional methods. Neanderthal neonate fossils, for example, are extremely rare, so Zollikofer did not want to risk copying his fragile specimen with the usual plaster-casting methods. With the printout, however, Zollikofer could explore the logistics of Neanderthal births. Along with the neonate skull, he printed out an adult, female Neanderthal pelvis and literally re-enacted 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 Neanderthal neonates counteracted that advantage (M. S. Ponce de León *et al. Proc. Natl Acad. Sci. USA* 105, 13764–13768; 2008). 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 — researchers 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 construction of balls and sticks.

Printed models help to reveal how molecules function.

at all. But in the short term, researchers see potential for printing out 3D cell structures far 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 fibrosis: an excess of hard fibrous tissue and scarring that arises from interactions between an organ's internal cells and its outer layer. 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 biomaterials 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 stem 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

**NATURE.COM**  
To see a 3D printer in action, go to: [go.nature.com/eq4t4z](http://go.nature.com/eq4t4z)

**THE REAL POWER OF 3D PRINTING LIES IN ITS ABILITY TO PUT SCIENCE INTO THE HANDS OF THE MANY.**

Others agree that the real power of 3D printing lies in its ability to put science into the hands of the many. Cronin 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 Olson, "the ability to make physical models has become democratized." ■ [SEE COMMENT PAGE](#)



Printouts of Neanderthal skulls from a child (left) and a neonate.

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

#### CUSTOM TOOLS

In the meantime, basic plastic 3D printers are starting to allow researchers to knock out customized tools. Leroy Cronin, 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. Szymes *et al. Nature Chem.* 4, 349–354; 2012). Cronin replaced the 'inks' in a \$2,000 commercially available printer with silicone-based shower sealant, a catalyst and reactants, 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 idea 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 Bayeve, an environmental engineer at Rensselaer 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 for more precise research — a task that previously required many hours on a lathe. Printing, he says, is much easier.

Perhaps more importantly, Bayeve can share his product just by publishing the design file. "The idea of being able to reproduce experiments described in the literature is taking on a new meaning," he says.

Others agree that the real power of 3D printing lies in its ability to put science into the hands of the many. Cronin 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 Olson, "the ability to make physical models has become democratized." ■ [SEE COMMENT PAGE](#)

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



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.

# 3D Printing Laboratory



# 3D Printing Laboratory

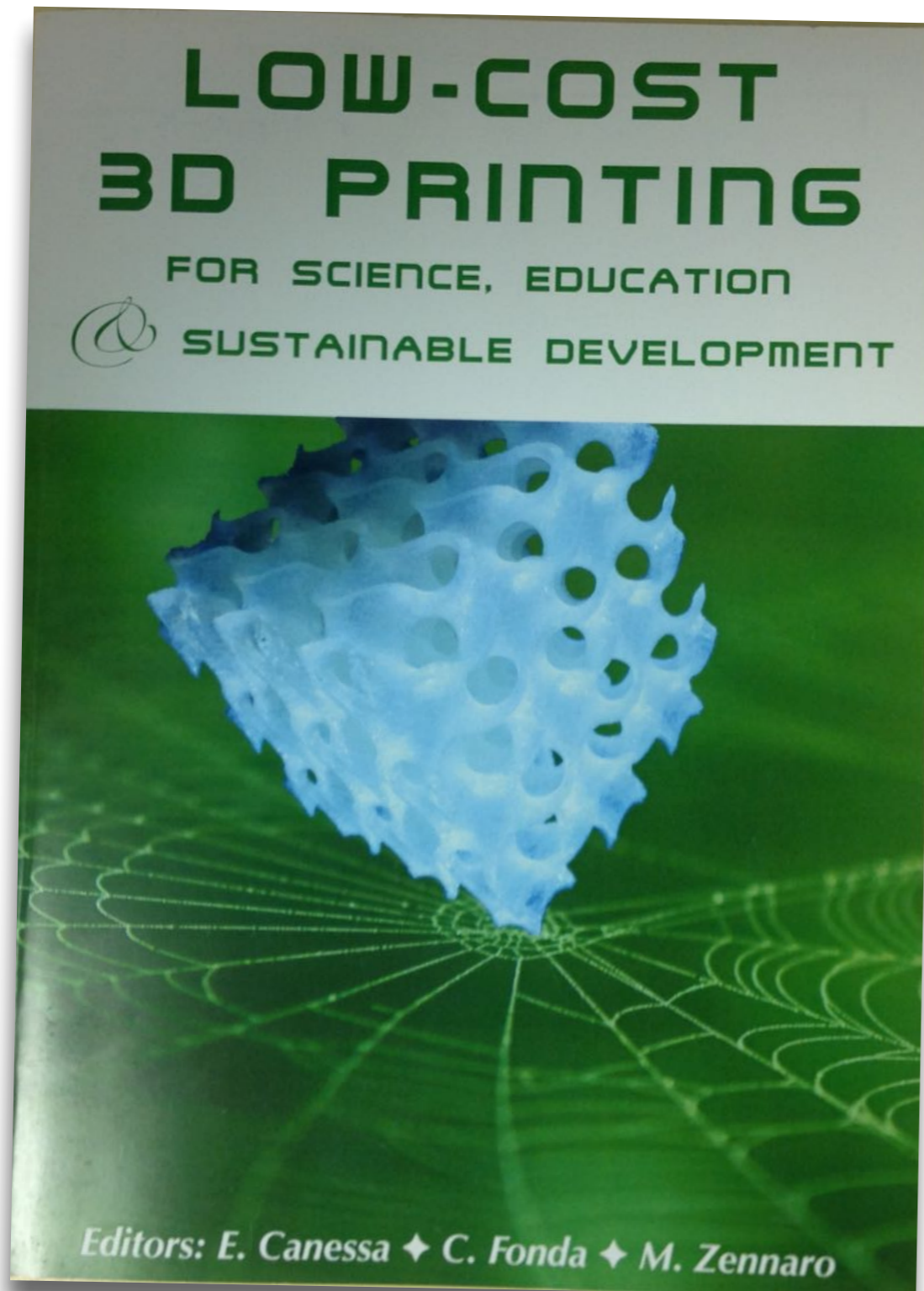


*"A once-shuttered warehouse is now a state-of-the-art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything"*

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



A free and open book (and eBook):



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



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## Low-cost 3D Printing

### for Science, Education & Sustainable Development

Low-cost, three-dimensional (3D) desktop printing, although still in its infancy, is rapidly making its way into schools and universities. The focus is that this cutting-edge 3D technology

will be used to create a new generation of scientists and engineers. 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**

# LOW-COST 3D PRINTING

## FOR SCIENCE, EDUCATION

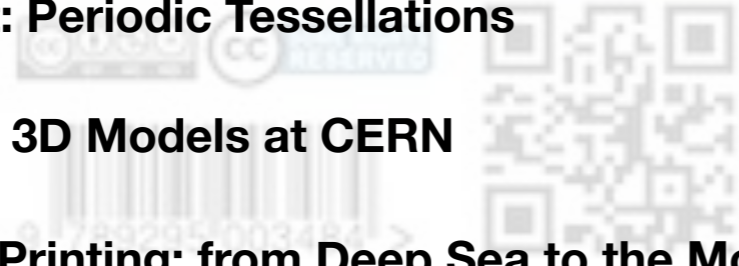
## SUSTAINABLE DEVELOPMENT

- **Trabecular Bone Modeling with Support of 3D Printing of Physical Replicas**
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- **Prehistoric Collections and 3D Printing for Education**
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- **Perpetual Plastic Project**

C. Fonda + M. Zennaro

Original cover photo courtesy of C. Fonda.  
Published by the ICTP © 2013

ISBN 92-95003-48-9





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 accessible, first overview of current research on 3D printing, sparks 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

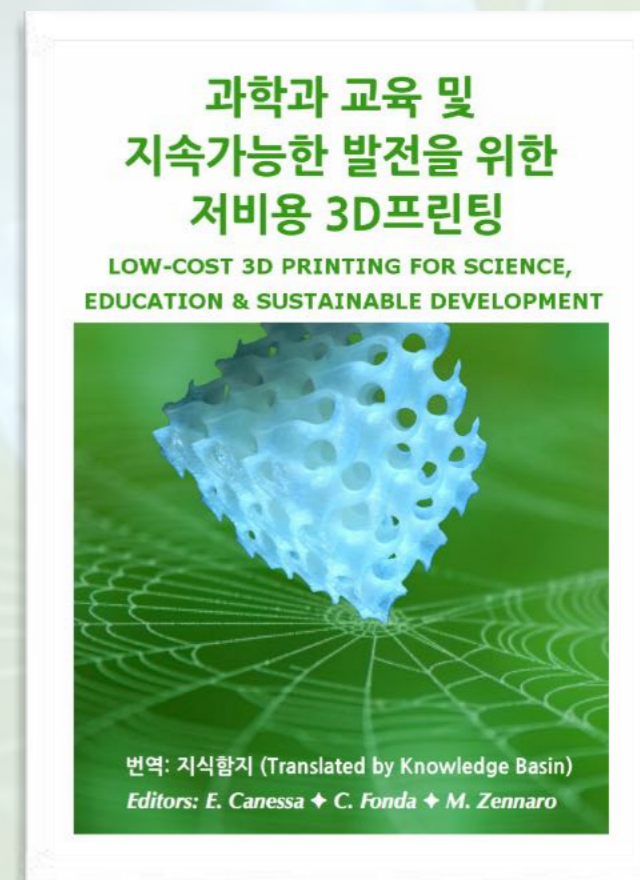
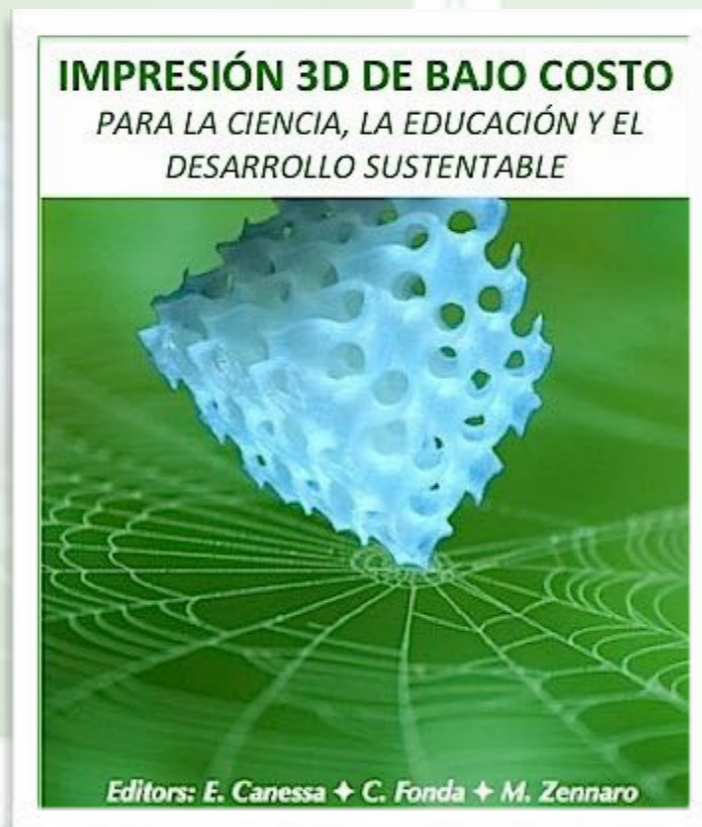


Photo courtesy of C. Fiori.  
Published by the ICTP, © 2013.

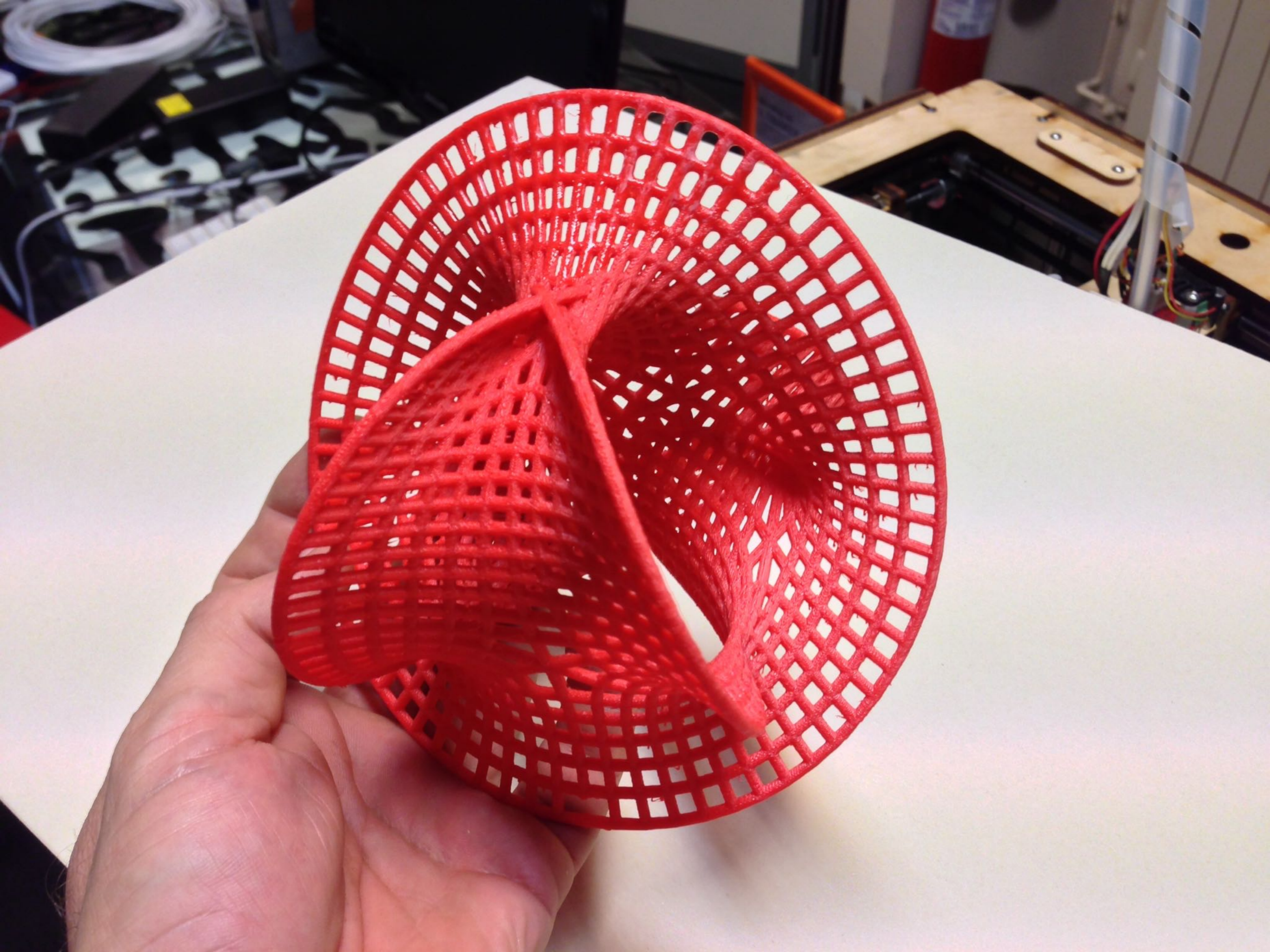
ISBN 92-95003-48-9



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

Russian, etc... (in preparation)

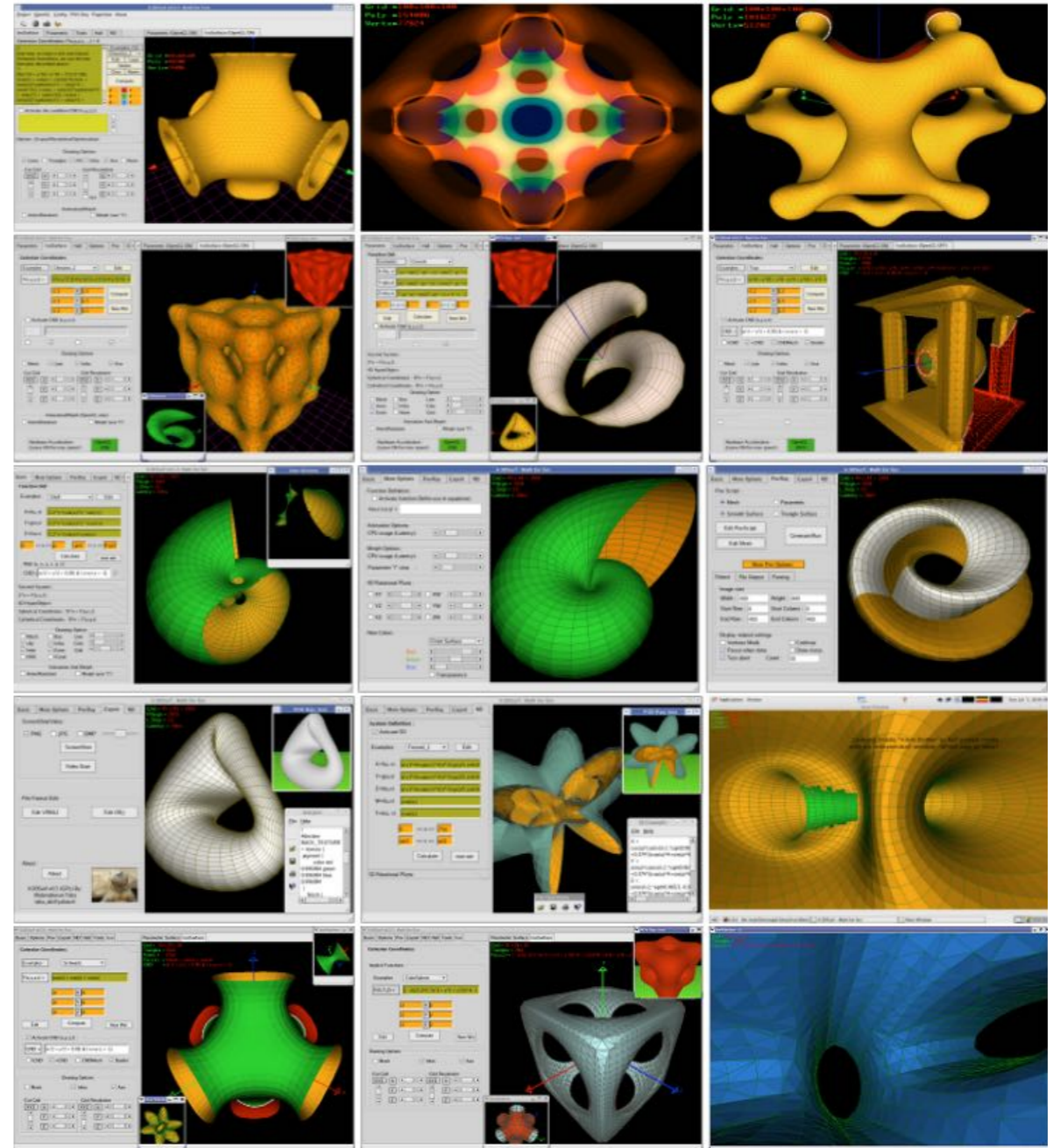
[sdu.ictp.it/3D](http://sdu.ictp.it/3D)





# K3DSurf

- K3DSurf is a program to visualize and manipulate mathematical models in 3, 4, 5 and 6 dimensions
- K3DSurf supports Parametric equations and Isosurfaces
- multiplatform (Win/OSX/Linux), free opensource software
- web: [k3dsurf.sourceforge.net](http://k3dsurf.sourceforge.net)



Cartesian Coordinates:  $F(x,y,z,t, \dots) = 0$ 

```

/*
And now, to make a tick and closed
Schwartz Isosurface, we use the two
formulas described above :
*/
if((x^10 + y^10 + z^10 < 3*(3.5^10)),
(cos(x) + cos(y) + cos(z))^((cos(x) +
sin(x)/(2*sqrt(sin(x)^2 + sin(y)^2 +
sin(z)^2))) + cos(y) + sin(y)/(2*sqrt(sin(x)^2
+ sin(y)^2 + sin(z)^2))) + cos(z) +
sin(z)/(2*sqrt(sin(x)^2 + sin(y)^2 +
sin(z)^2)))

```

Examples (51)

Closelso\_2

Edit Load

Delete

Clear Newwin

Compute

-4 X 4

-4 Y 4

-4 Z 4

 Activate the condition CND [x,y,z,t] :

 CND  
 CND  
 Border  
 Mesh

Options: (Export/Resolution/Optimisation)

Drawing Options

 Lines  Triangles  Fill  Infos  Axe  Norm

Cut Grid

 XYZ  X  Y  Z

Grid Resolution

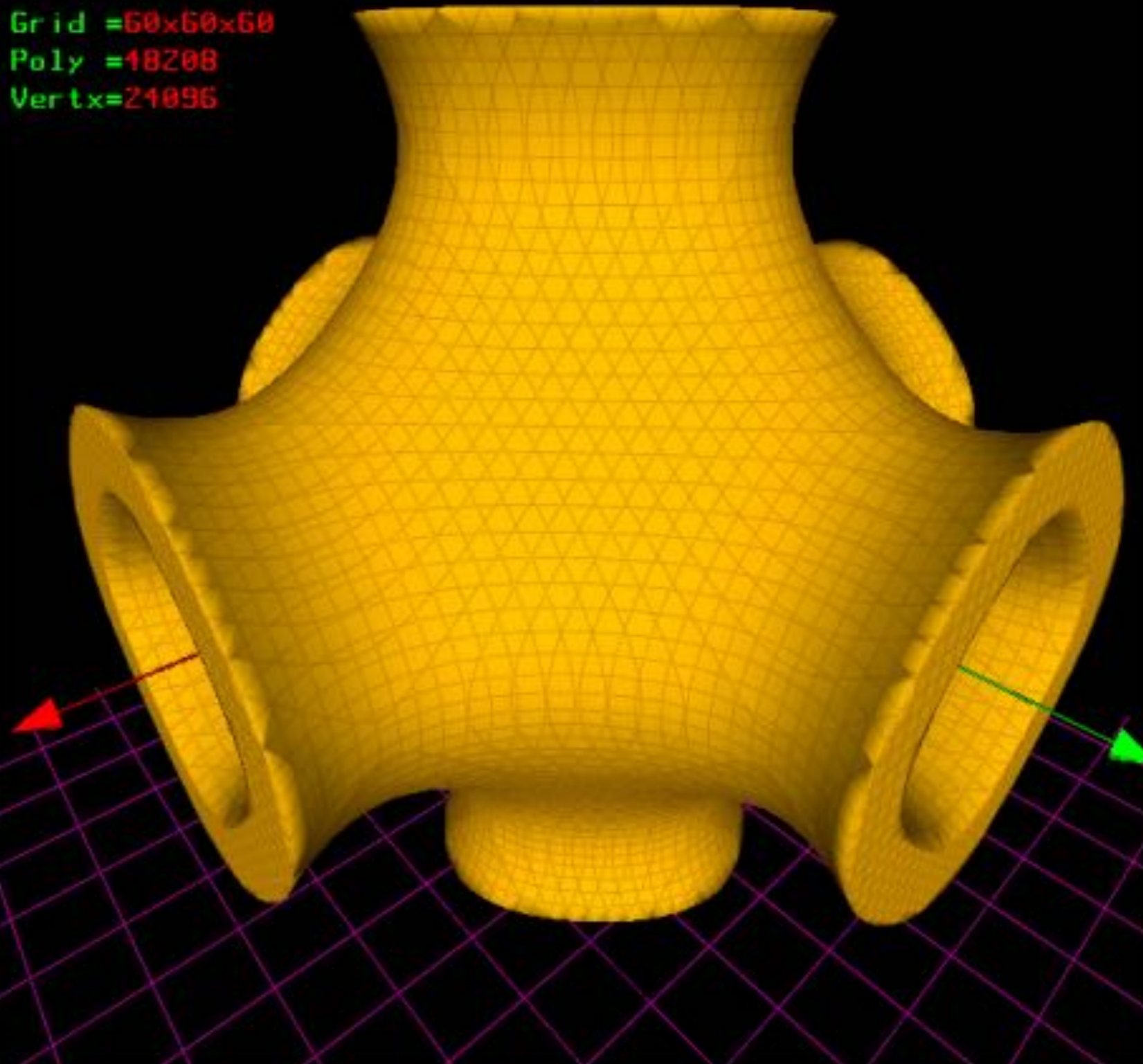
 xyz  X  Y  Z

Animation/Morph:

 Anim(Rotation)

 Morph (use "t")

Grid = 60x60x60  
Poly = 18208  
Vertx = 21896



Cartesian Coordinates:

Implicit Functions :

Examples CubeSphere

F(X,Y,Z) =  $1 - ((1/2.3)^2 * (x^2 + y^2 + z^2))^6 - ($

-2 X 2

-2 Y 2

-2 Z 2

Edit Compute New Win

Drawing Options

Mesh  Infos  Axe

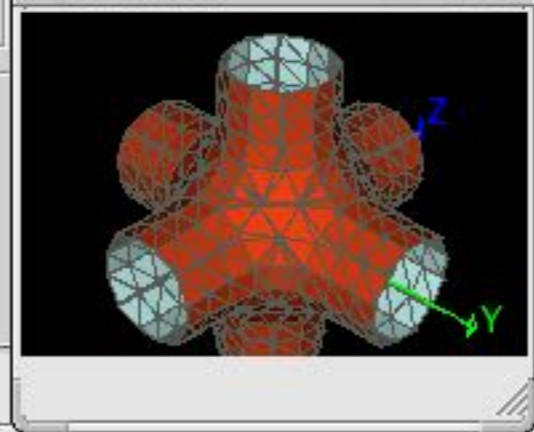
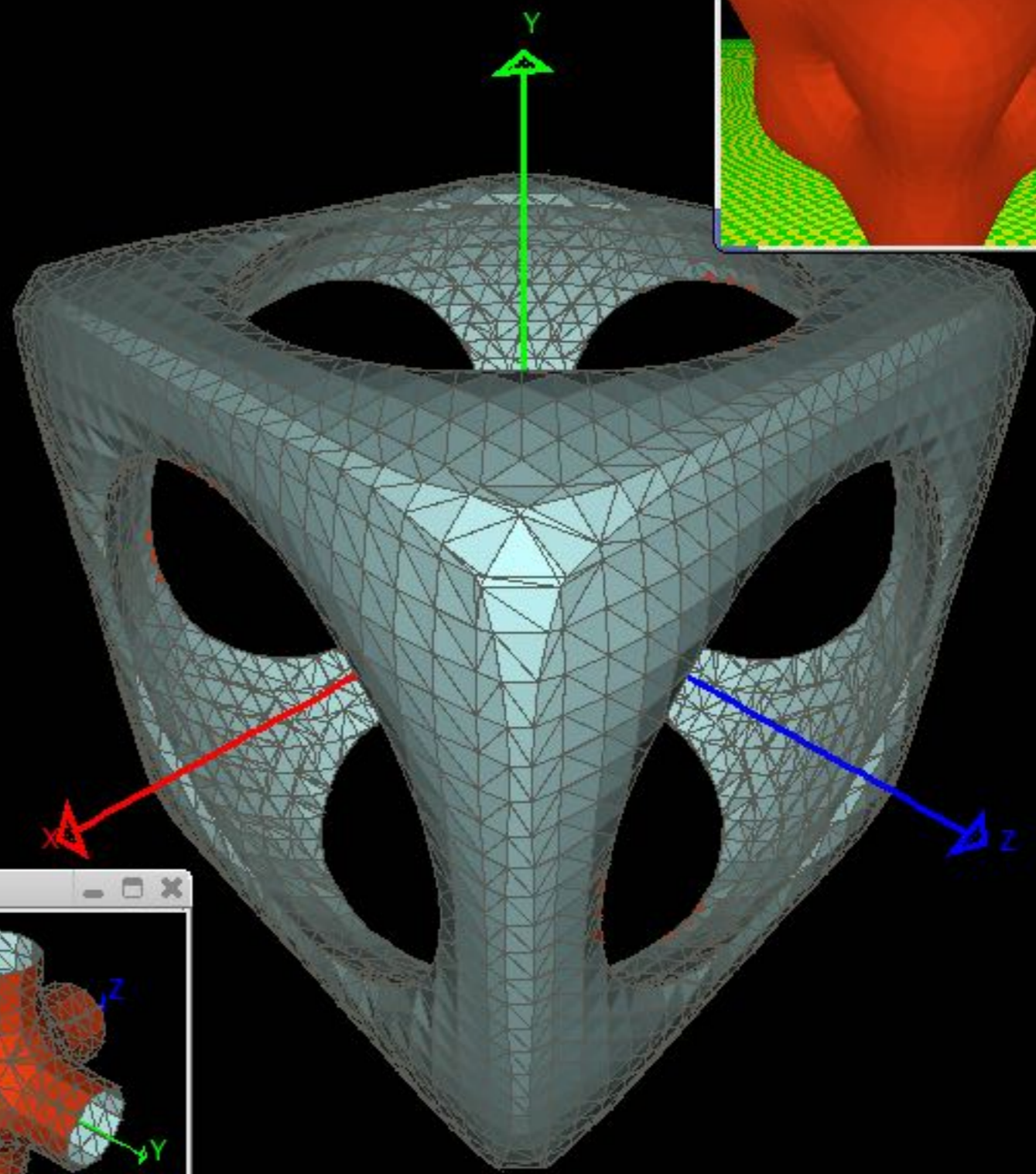
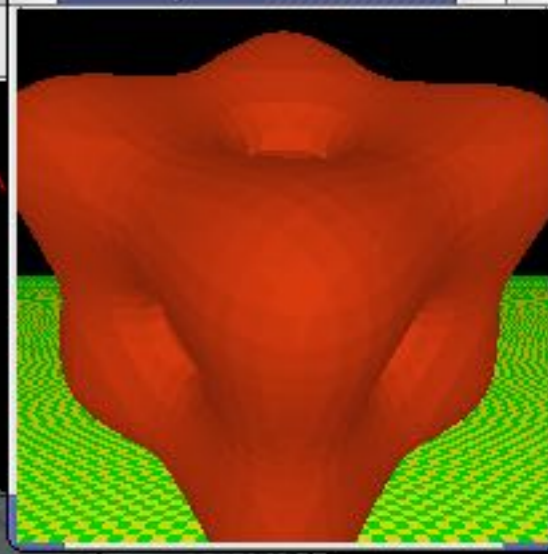
Cut Grid

XYZ X Y Z

Grid Resolution

XYZ X Y Z

Grid = 26 x 26 x 26  
Triangles = 7861  
F(x,y,z) =  $1 - ((1/2.3)^2 * (x^2 + y^2 + z^2))^6 - ( (1/2)^8 * (x^8 + y^8 + z^8)$



K3DSurf : Math for fun

Basic More Options PovRay Export ND

ScreenShot/Video :

PNG  JPG  BMP

ScreenShot

Video Start

File Format Edit:

Edit VRML2

Edit OBJ

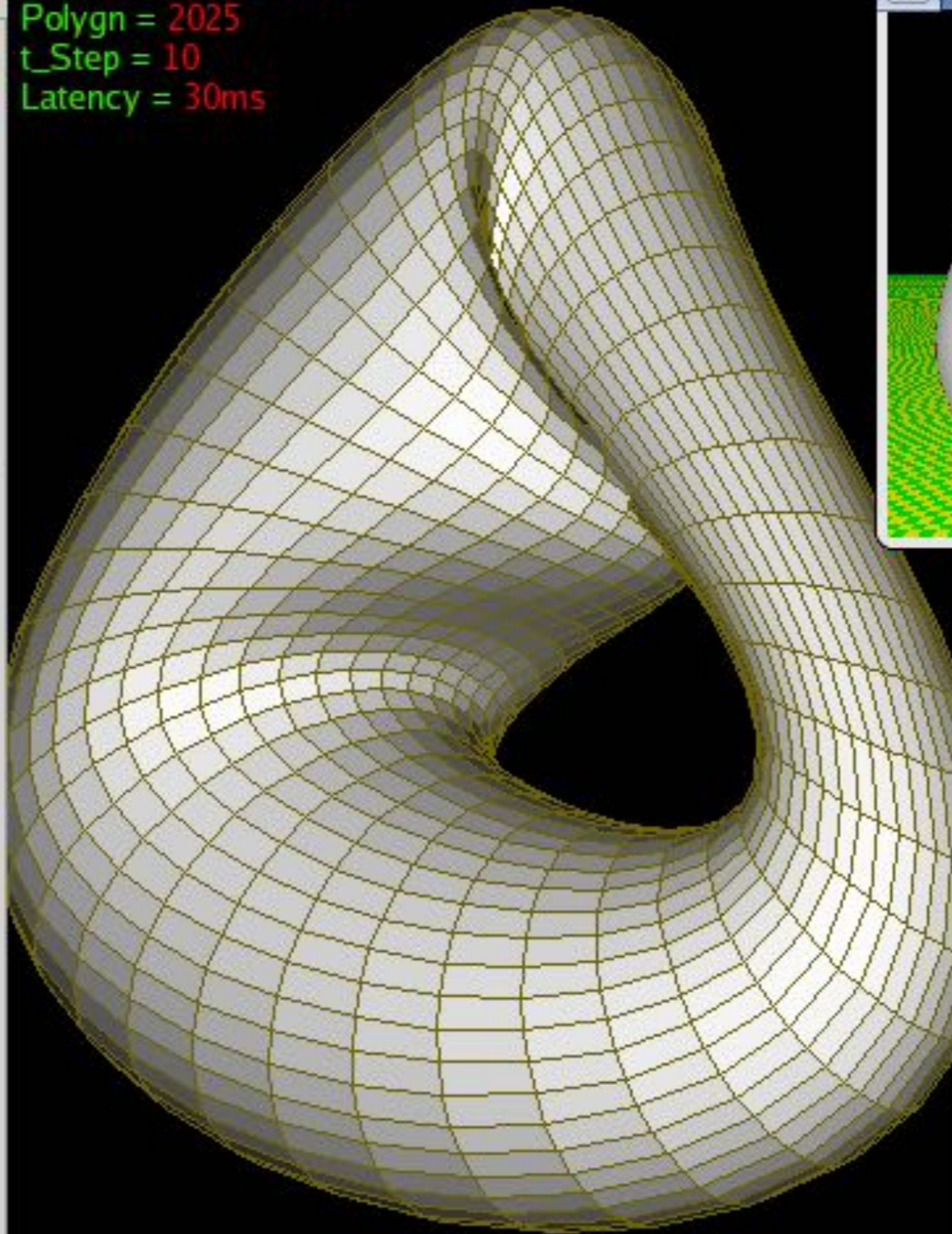
About :

About

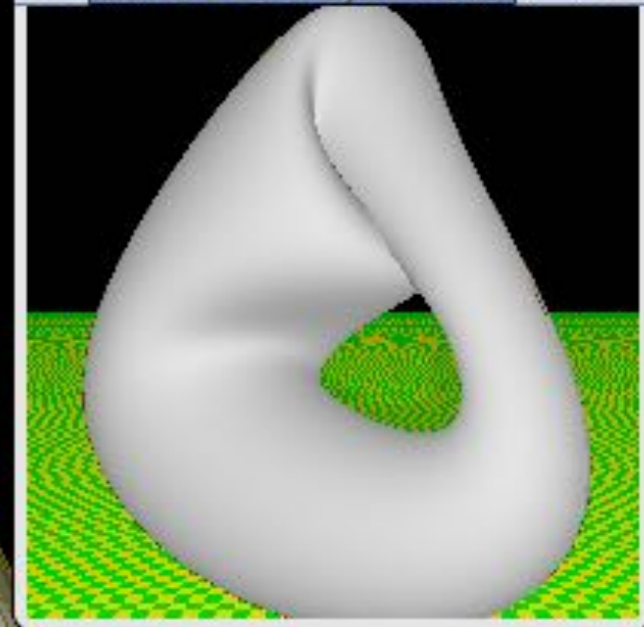
K3DSurf v0.5 (GPL) By:  
Abderrahman Taha  
taha\_ab@yahoo.fr



Grid = 45 x 45 = 2025  
Polygn = 2025  
t\_Step = 10  
Latency = 30ms



POV-Ray: test



test.pov

File Help

```
}  
#declare  
BACK_TEXTURE  
= texture {  
  pigment {  
    color red  
    0.996094 green  
    0.996094 blue  
    0.996094  
  }  
  finish {
```

# Tutorial: “Math to Jewel”

- See: “**From Math to Jewel: an Example**”  
an article by *Gaya Fior*

in the free open book on “Low-cost 3D Printing for Science, Education and Sustainable Development”



<http://sdu.ictp.it/3D/book.html>

## From Math to Jewel: an Example

Gaya Fior

ICTP Science Dissemination Unit collaborator

and 32b.it, Trieste, Italy

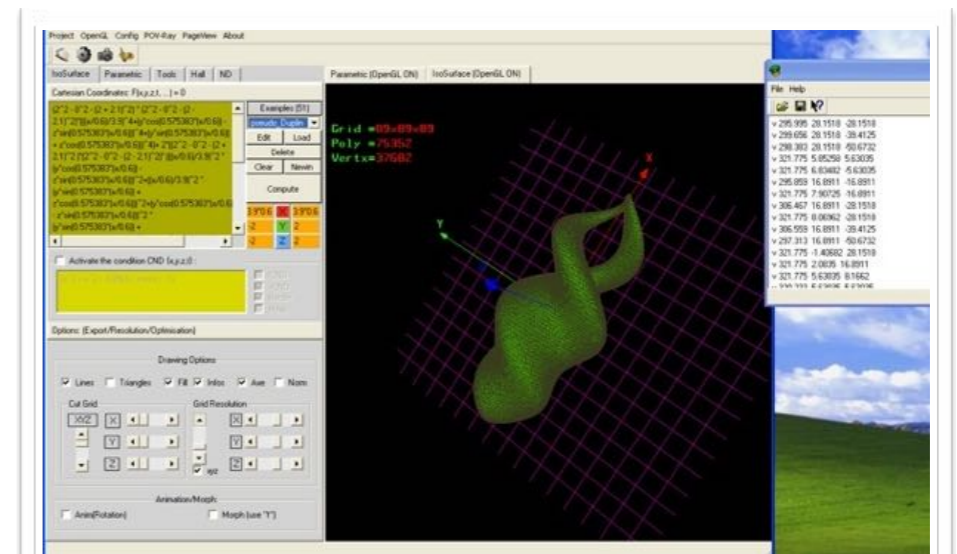
[gfiorfior@gmail.com](mailto:gfiorfior@gmail.com)

3D printing gives the possibility to transform what you can imagine into a tangible object that then can be also worn and showed off.

We will see how using just free tools available on the web we can transform a mathematical isosurface into an object that can be then used for instructional or decorative purposes.

The first step is to download a software that lets us visualize and manipulate mathematical surfaces in three dimensions. A good choice is K3DSurf<sup>1</sup>, a free tool that works on multiple platforms and supports parametric equations and isosurfaces.

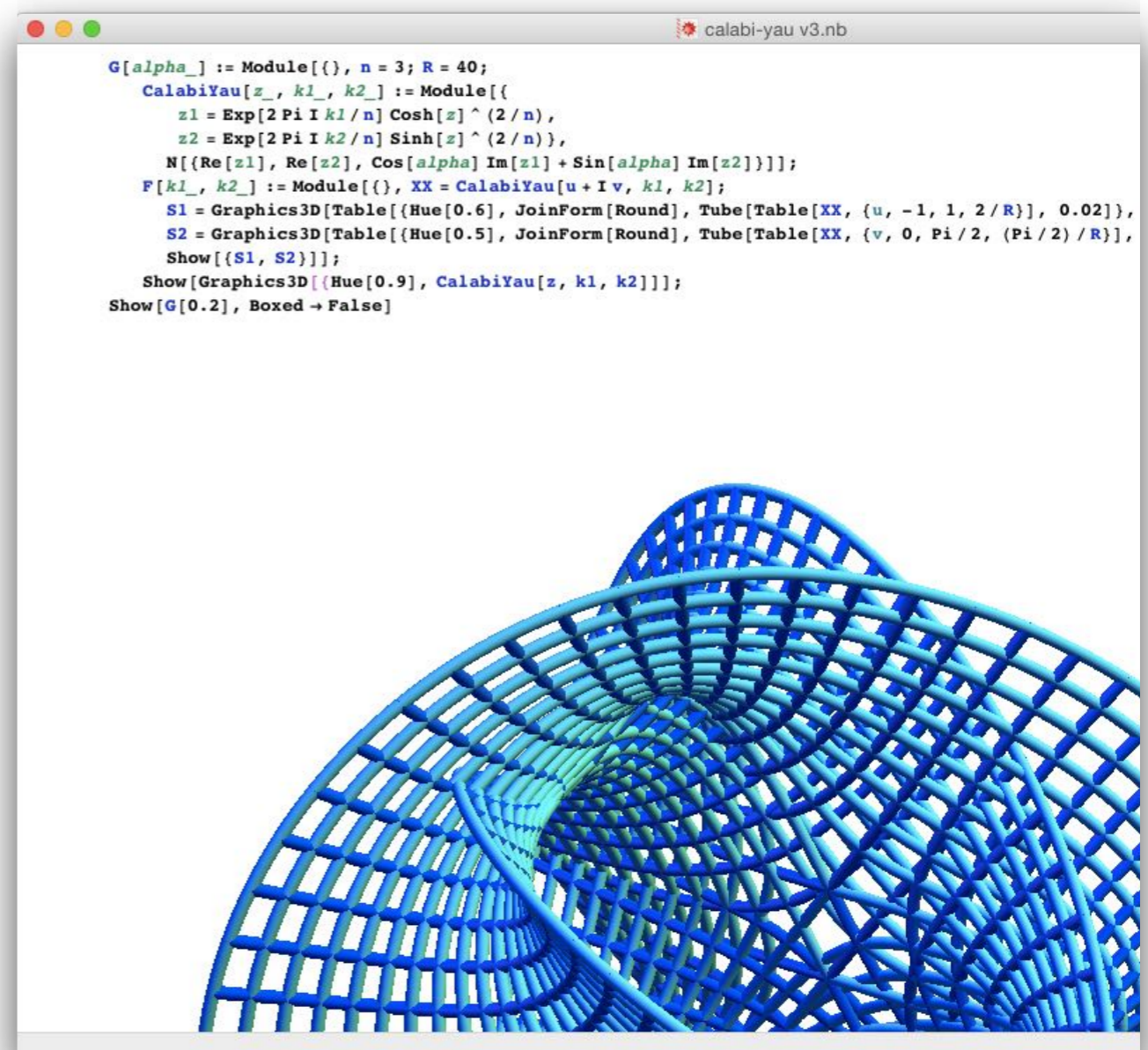
The software comes with more than 50 built-in examples, so you can start modifying the parameters in the provided equations to study the effects on the rendering result.



The K3DSurf interface

# Mathematica™

- Mathematica™ doesn't need any introduction, is the most powerful tool for mathematics
- it can generate and export 3D models (as STL, but it isn't always a correct manifold)
- [www.wolfram.com/mathematica](http://www.wolfram.com/mathematica)

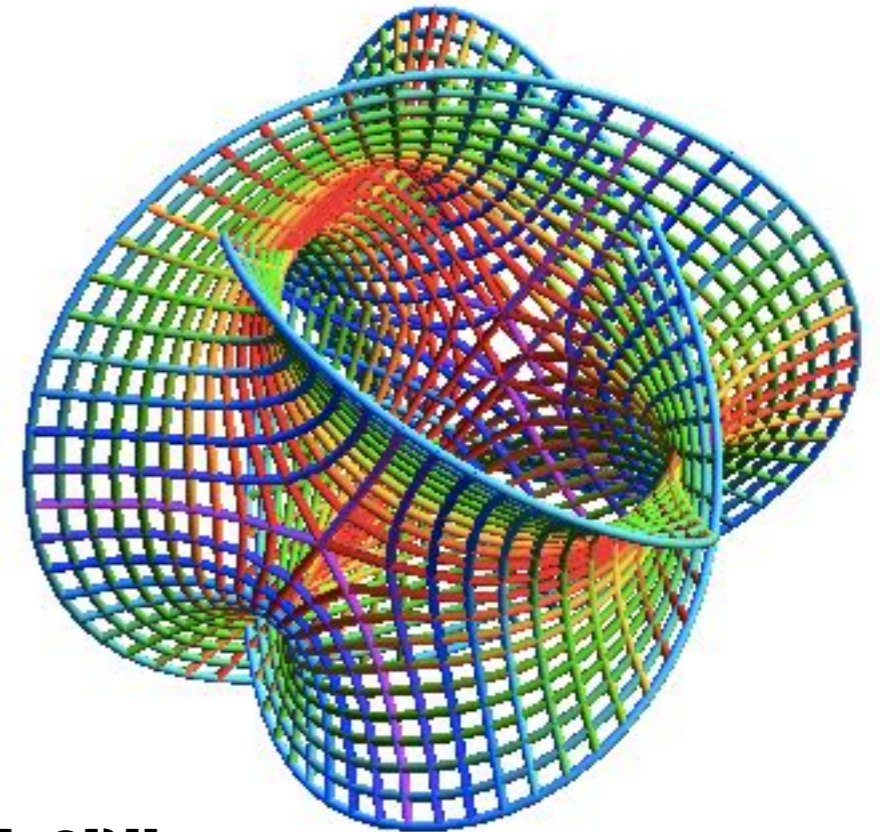


- `Import` and `Export` fully support the STL file format.

### ▼ Import and Export

- `Import ["file.stl"]` imports an STL file as a `Graphics3D` object.
  - `Export ["file.stl", expr]` exports a `Graphics3D` expression to a binary STL file.
- 
- `Import ["file.stl"]` returns an expression of the form `Graphics3D [GraphicsComplex [vertices, primitives, opts]]`.
  - `Export ["file.stl", Graphics3D [...]]` creates an STL file representing a solid physical model.
- 
- `Import ["file.stl", elem]` imports the specified element from an STL file.
  - `Import ["file.stl", {elem, suba, subb, ...}]` imports a subelement.
  - `Import ["file.stl", {{elem1, elem2, ...}}]` imports multiple elements.
  - The import format can be specified with `Import ["file", "STL"]` or `Import ["file", {"STL", elem, ...}]`.
- 
- `Export ["file.stl", expr, elem]` creates a binary STL file by treating `expr` as specifying element `elem`.
  - `Export ["file.stl", {expr1, expr2, ...}, {{elem1, elem2, ...}}]` treats each `expri` as specifying the corresponding `elemi`.
  - `Export ["file.stl", expr, opt1 -> val1, ...]` exports `expr` with the specified option elements taken to have the specified values.
  - `Export ["file.stl", {elem1 -> expr1, elem2 -> expr2, ...}, "Rules"]` uses rules to specify the elements to be exported.
-

# Calabi-Yau manifold (used in string theory)



```
G[alpha_] := Module[{}, n = 3; R = 40;
  CalabiYau[z_, k1_, k2_] := Module[{
    z1 = Exp[2 Pi I k1/n] Cosh[z]^(2/n),
    z2 = Exp[2 Pi I k2/n] Sinh[z]^(2/n)},
    N[{Re[z1], Re[z2], Cos[alpha] Im[z1] + Sin[alpha] Im[z2]}]];
  F[k1_, k2_] := Module[{}, XX = CalabiYau[u + I v, k1, k2];
  S1 =
  Graphics3D[
    Table[{Hue[0.6], JoinForm[Round],
      Tube[Table[XX, {u, -1, 1, 2/R}], 0.02]}, {v, 0, Pi/2, Pi/20}]];
  S2 =
  Graphics3D[
    Table[{Hue[0.5], JoinForm[Round],
      Tube[Table[XX, {v, 0, Pi/2, (Pi/2)/R}], 0.02]}, {u, -1, 1, 0.1}]];
  Show[{S1, S2}]];
  Show[Graphics3D[{Hue[0.9], CalabiYau[z, k1, k2]}]];
  Show[G[0.2], Boxed -> False]
```



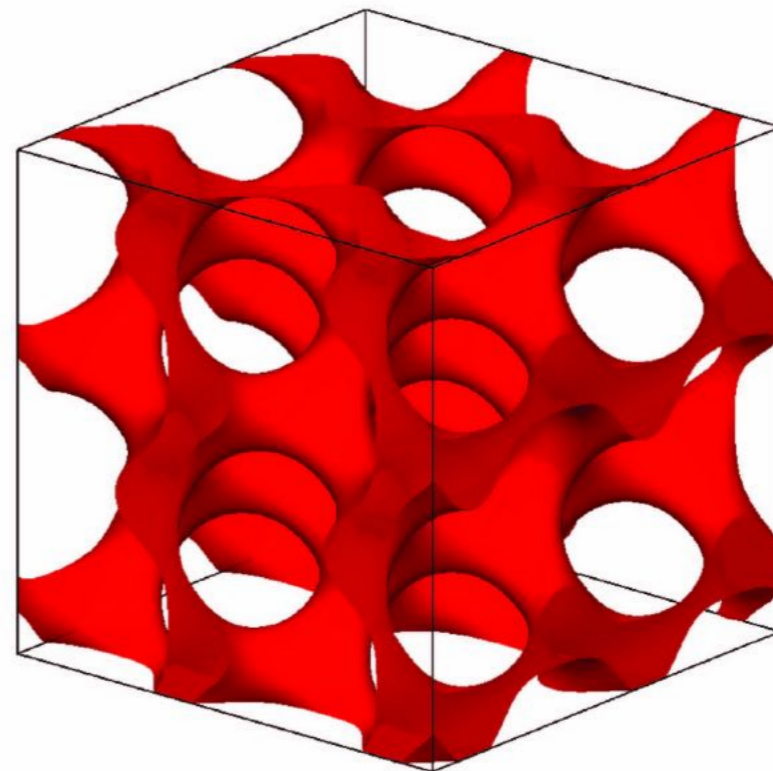


# Something new

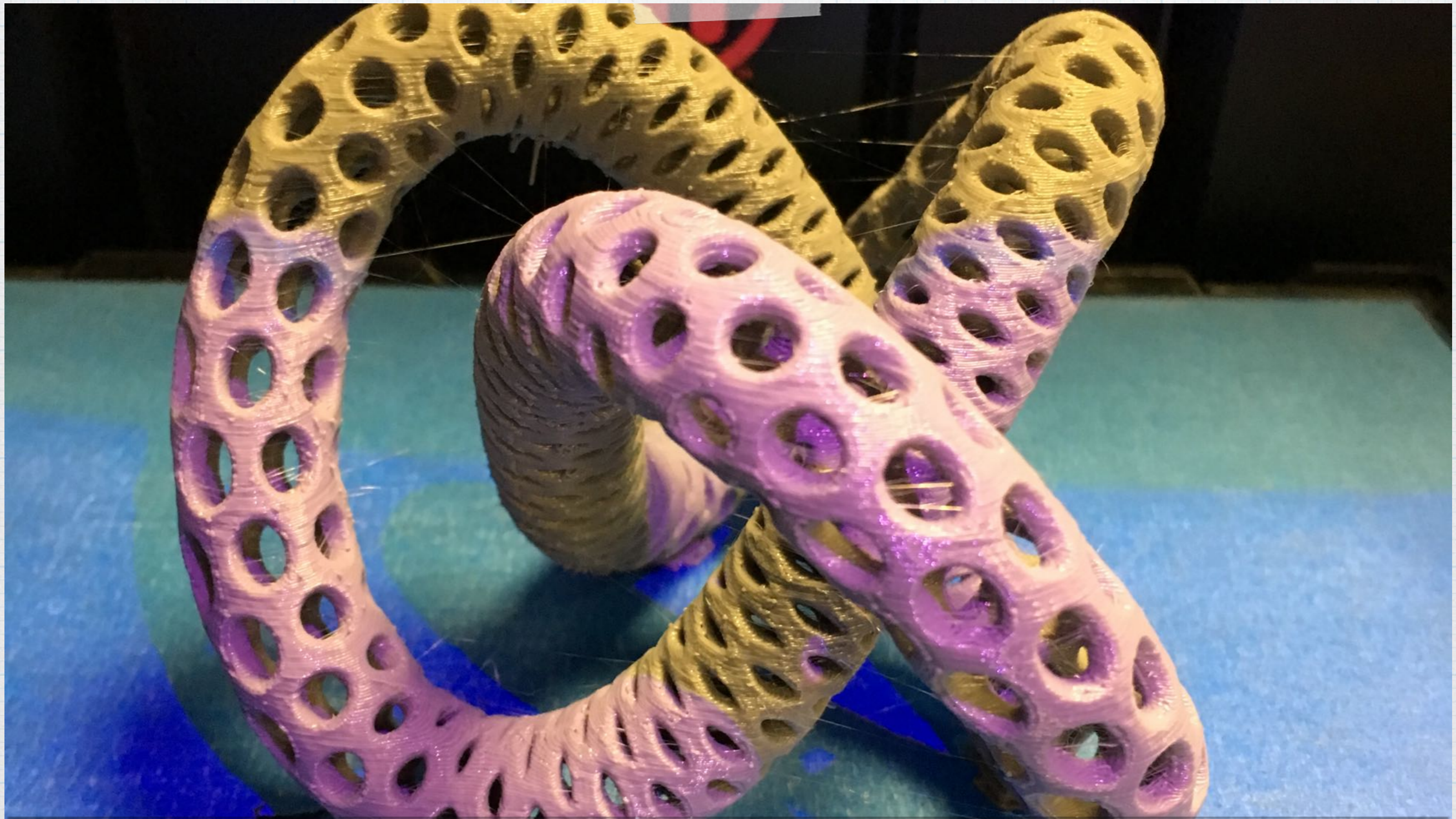
## "impossible" objects

- they can be modeled but *not manufactured* with traditional means
- 3D printers open a whole new world of possibilities

The gyroid is a complex cubic structure based on a surface that divides space into two separate volumes that are interpenetrating and contain various spirals. Pores and the superconducting material have structural dimensions of only around 10 nanometers, which could lead to entirely novel property profiles of superconductors.



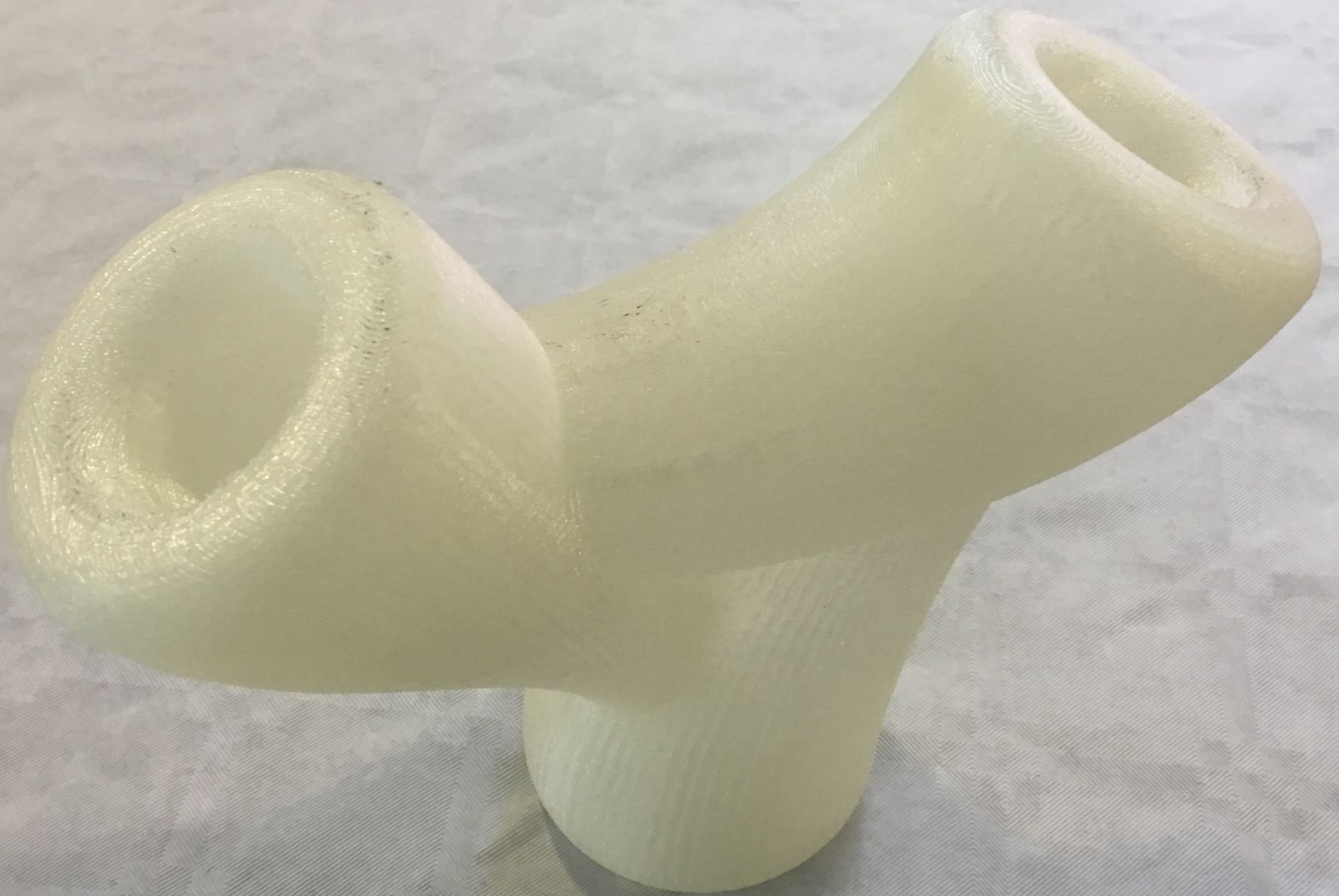
# Impossible objects





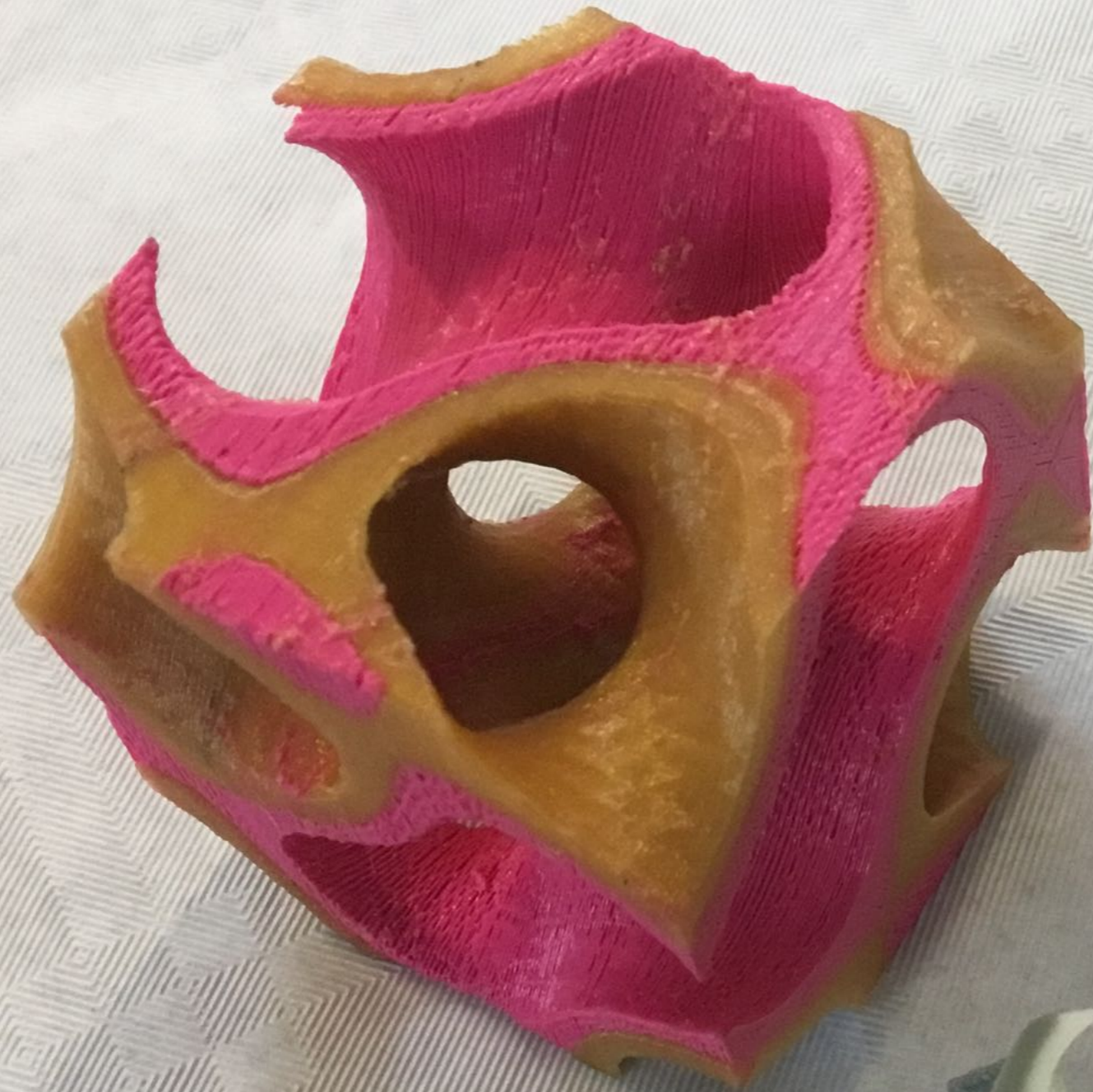


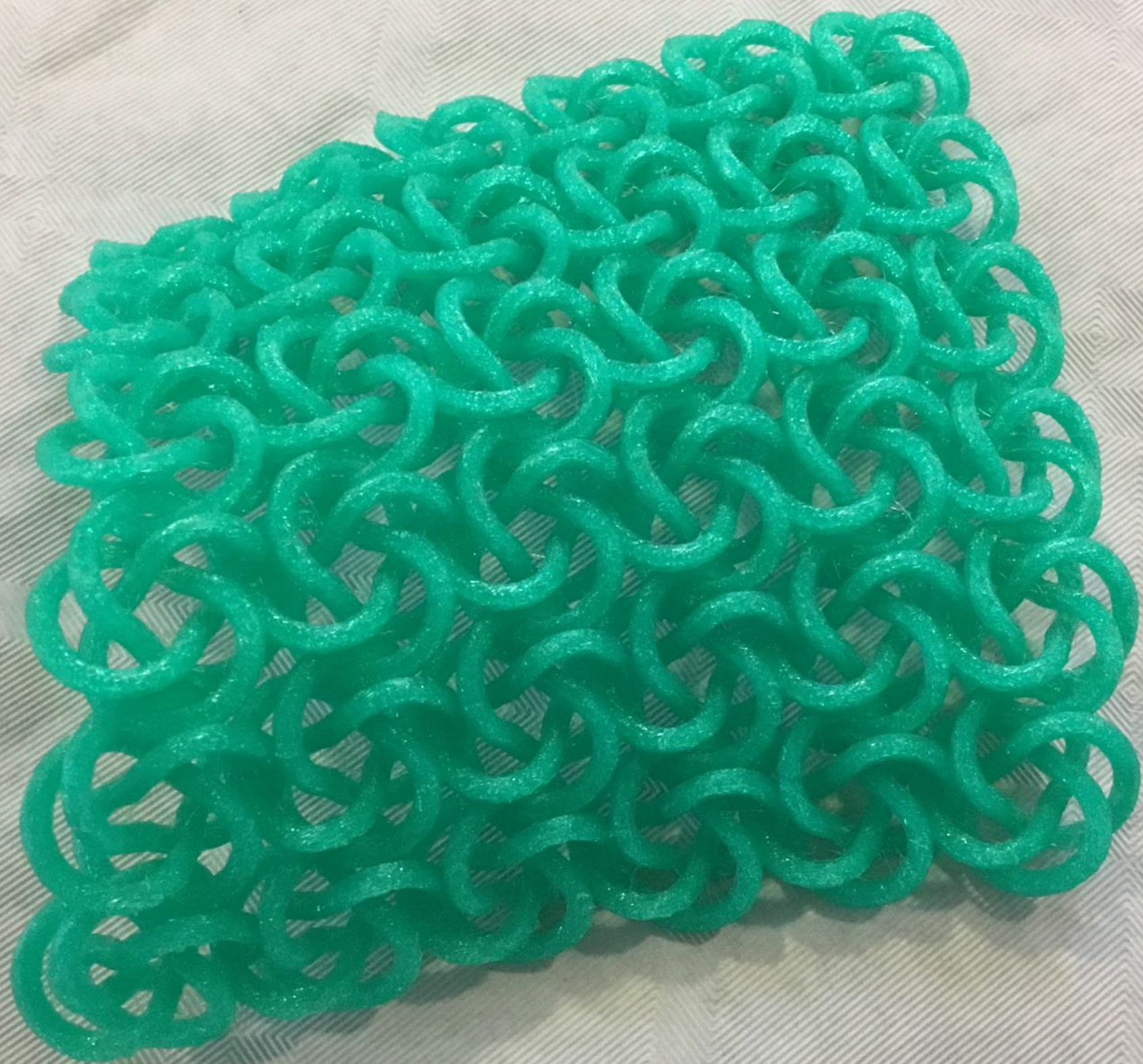


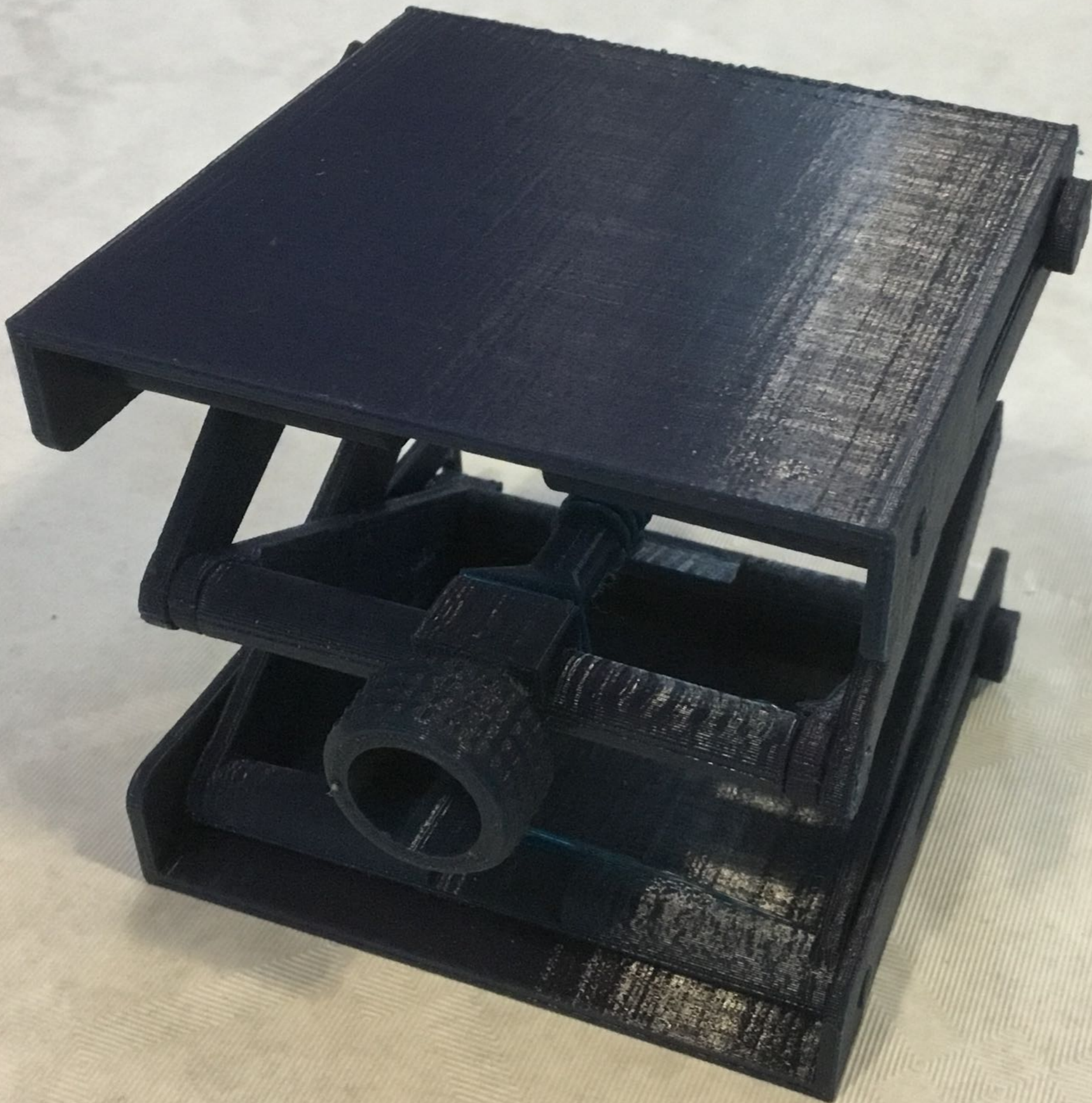






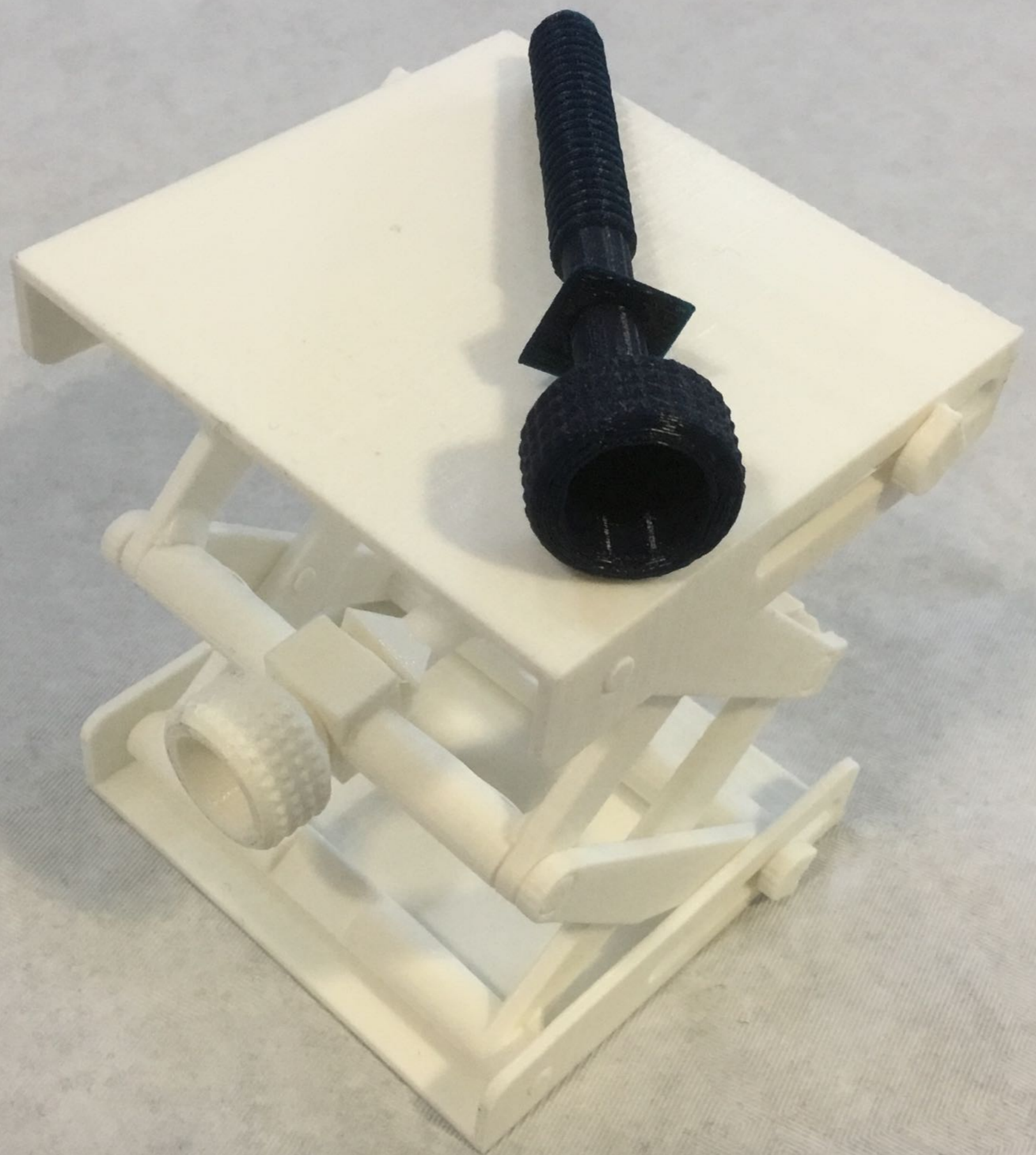


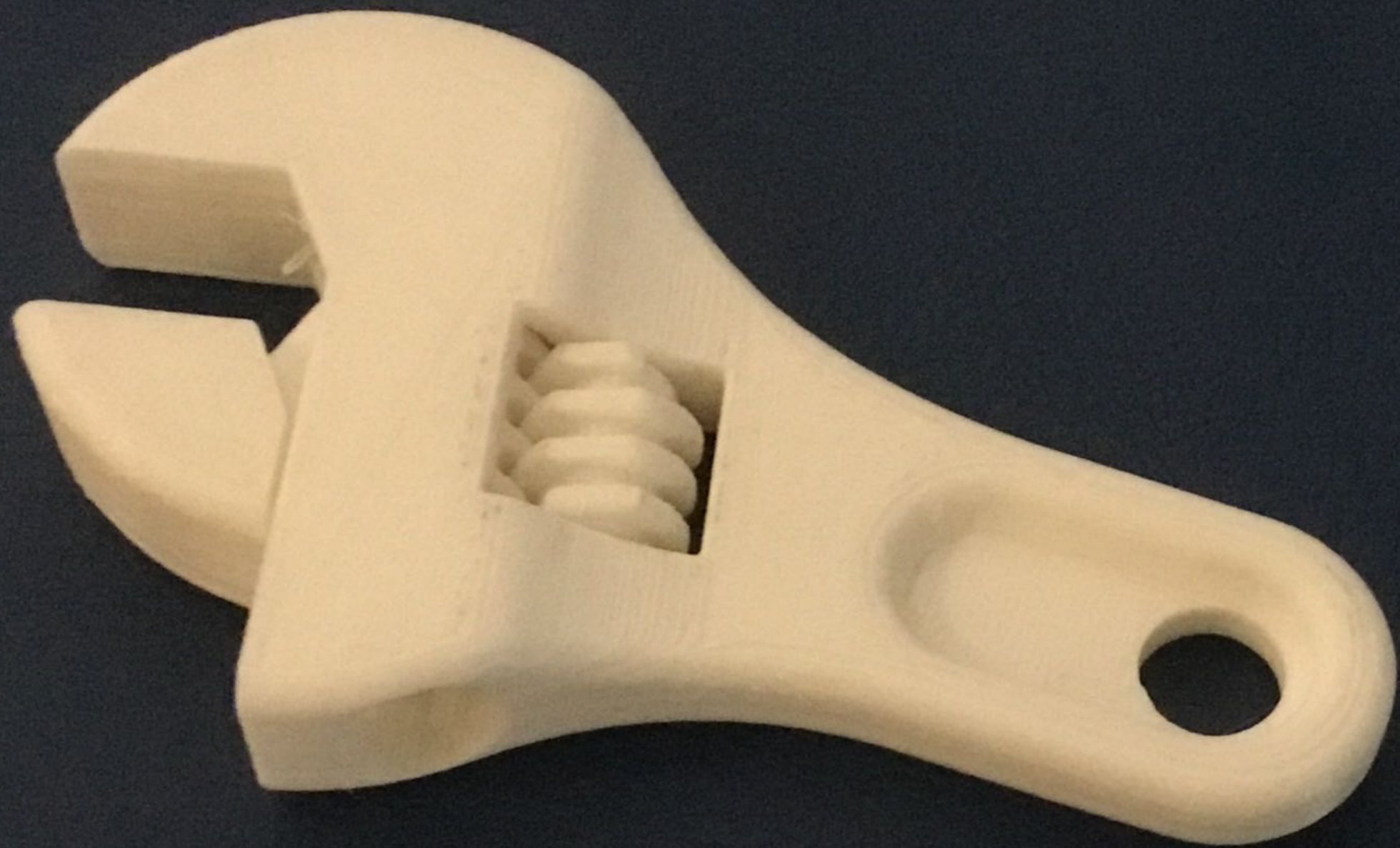




It  
looks  
easy...

One  
single  
print!





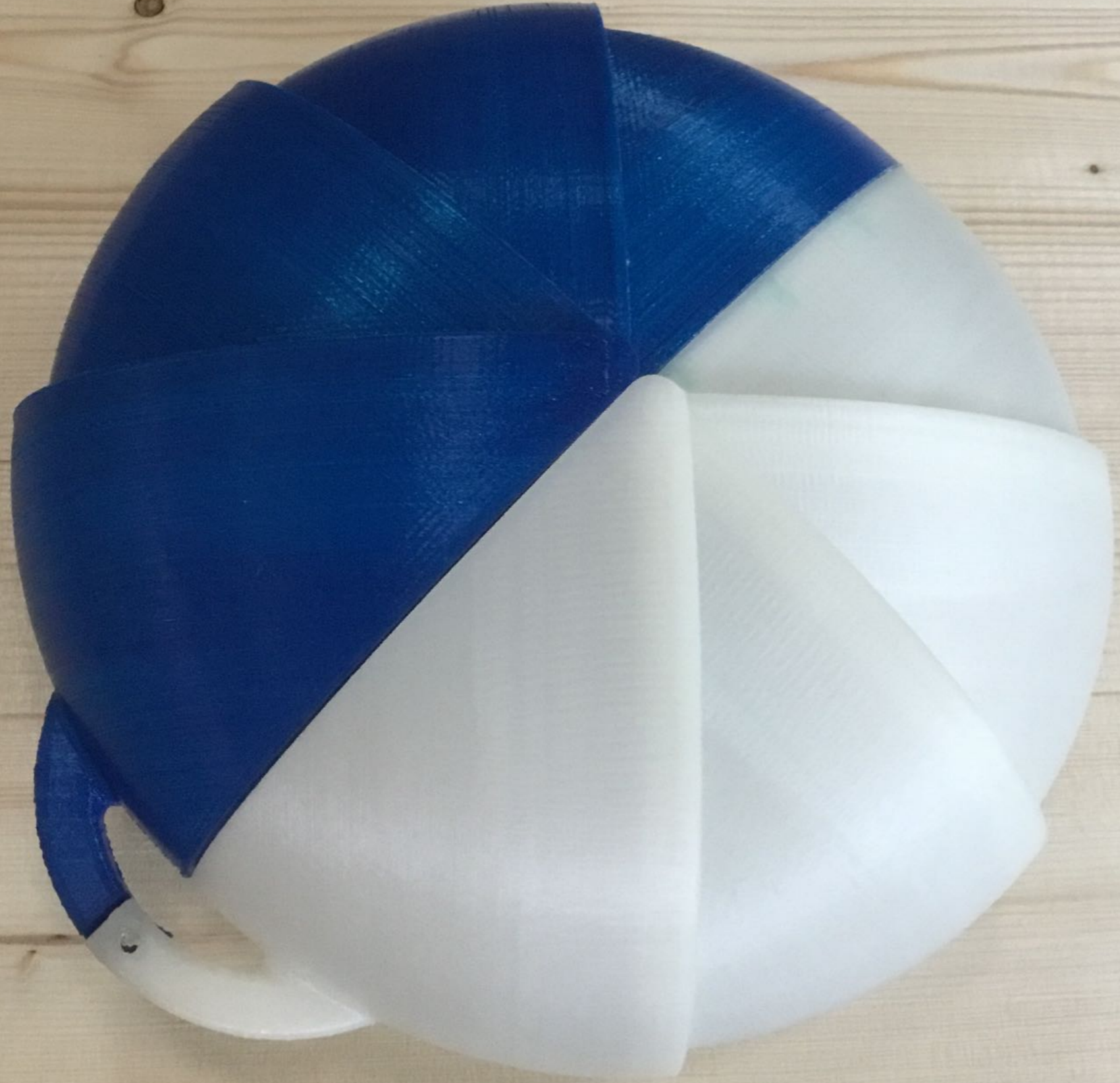


One  
single  
print!









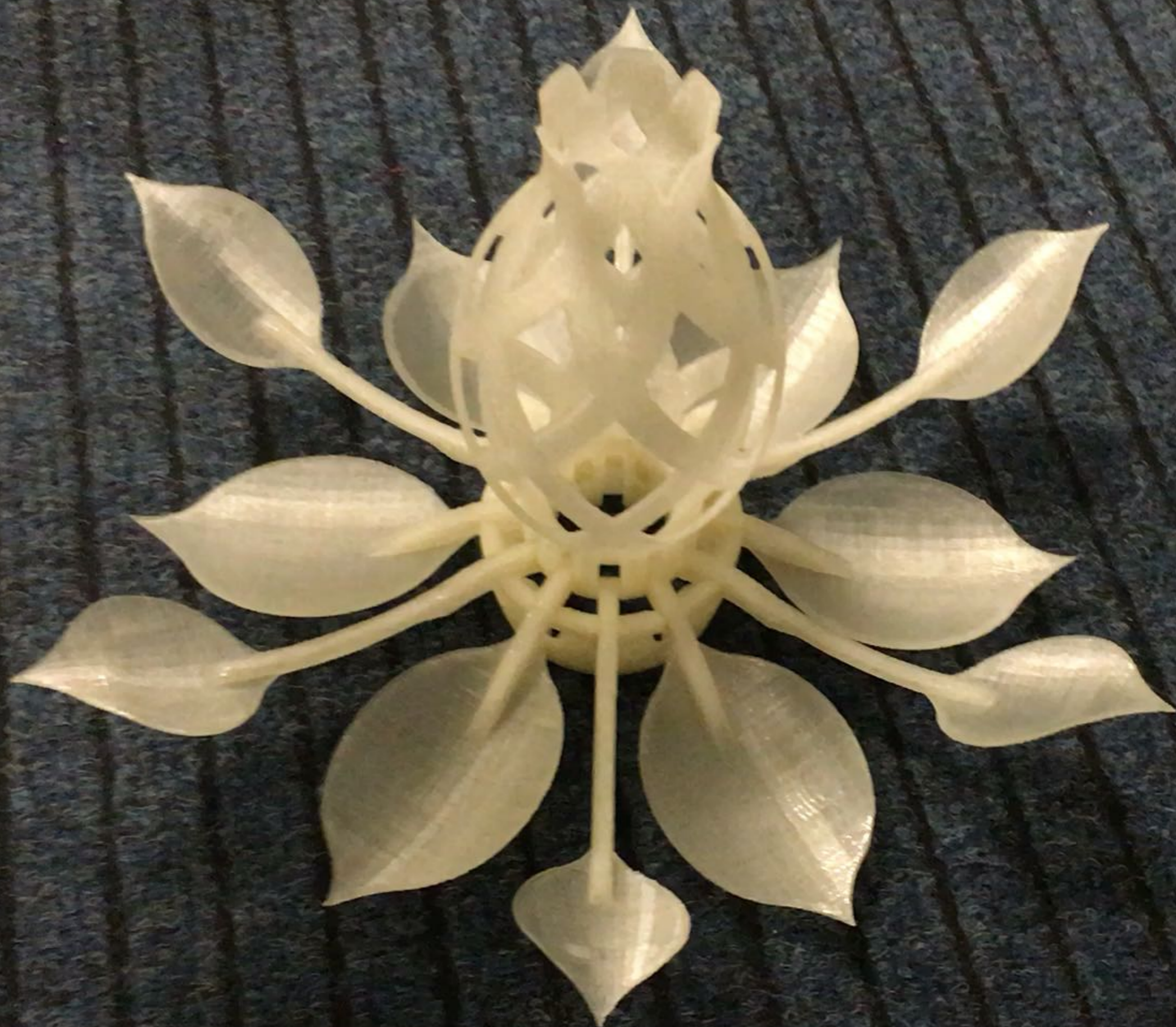












“Now it's up to you to creating something new.”

[cfonda@ictp.it](mailto:cfonda@ictp.it)

Carlo Fonda, ICTP Scientific Fablab