ICTP SCIENTIFIC FABRICATION LABORATORY
scifablab.ictp.it

Things you ~~cannot make~~ only can 3D-print

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

Carlo Fonda – cfonda@ictp.it
ICTP Scientific FabLab – scifablab.ictp.it
International Centre for Theoretical Physics
(ICTP) Trieste, Italy

Creative Commons Attribution-ShareAlike 4.0 International License
http://creativecommons.org/licenses/by-sa/4.0/

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$+)

- 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).

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

Low-cost *personal* 3D printers

cost: from 300 to 3000 USD

Open source + Open Hardware

- Low-cost printers use a plastic filament (ABS or PLA, 1.75 or 3mm thickness)
- 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)

6/49

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

7/49

Cartesian Coordinates

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

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

8/49

3D Printing Mechanics

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

Makerbot Replicator

- Third generation printer (the first two were the *Cupcake* and the *Thing-o-Matic*)

- Single or *Dual head* (can print in two colors, or two plastic types)

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

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

Printrbot

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

Not only from U.S.: the Ultimaker

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

The Cube

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

The Cube ($1299)

And many more...

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

Laser + liquid resin

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

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

Pro only

first personal
(for hackers)

really personal
(mass produced)

?

???

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...

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

- 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)

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

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

http://n-e-r-v-o-u-s.com

http://toxiclibs.org/2011/12/metworks-workshop-facade/

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

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
```

By Peter Uithoven @ Fablab Amersfoort (CC-BY)

Thingiverse & C.

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

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

#6 - Finishing

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

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

A world of plastic

don’t pollute,
3D-print!

Many types of plastics

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

Filament

- Filament comes in two standard diameters, **1.75 mm** and **3.0 mm**. The 3.0 mm filament is somehow an older standard and is slowly being upstaged by the 1.75 mm because it can be pushed slightly more easily, controlled a little better and sometimes leaves fewer tails hanging off the sides of your object.

- Cost: around 30$ (25€) per kg.

- 1g of printed object ~ 0.03 cents

- active development of systems for **low-cost filament production "at home"**, starting from plastic pellets or –even better– from recycling of plastic waste.

Recycling plastic

www.perpetualplasticproject.com

- make 3D-printed objects from recycled plastic

3DP as Service

www.makexyz.com

www.3dhubs.com

3DP as Service

www.3ditaly.it

www.shapeways.com

http://i.materialise.com/

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

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

Cosmo Wenman

Cloning objects

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

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

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 specilista 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 - +39 3479441717

Giorgio Faganello, Carlo C
Manuel Belgrano, Giulia Ru
Pozzi, Giovanni Cioffi & And
Lenarda
The International Journal of Cardiovascular Imaging
CARDIOVASC
IMAGING
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 demonstrtes 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)

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.

Thank you for you 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 ni nj nk
outer loop
vertex v1x v1y v1z
vertex v2x v2y v2z
vertex v3x v3y v3z
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**.

User Ortho
Delete
Vertices
Edges
Faces
Only Edges & Faces
Only Faces
Dissolve Vertices
Dissolve Edges
Dissolve Faces
Limited Dissolve
Edge Collapse
Edge Loops
(0) Cube.001

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.

Repetier-Host V1.0.6 - MAKE_Robot_Arms_Down_Supportless_V4.1
File
Vista
Configurazione
Stampante
Strumenti
Aiuto
Disconnetti
Carica
Salva lavoro
Lavoro in pausa
Ferma lavoro
Mostra/nascondi Log
Mostra filamento
Nascondi percorso
Impostazioni stampante
Easy Mode
S T O P !!!
Visualizzazione 3D
Curva Temperatura
Posizione oggetto
Slicer
Anteprima
Controllo manuale
SD Card
Gruppo oggetto 7
MAKE_Robot_Arms_Down_Supportless_V4.1
1
L'oggetto è "non-manifold". Ciò significa in sostanza, che non è "a tenuta stagna". Questo, normalmente, causa problemi durante lo slicing, causando risultati indesiderati. Si consiglia vivamente di riparare il file. Un servizio di riparazione libero è: https://netfabb.azurewebsites.net

Warning!

NON-MANIFOLD
MANIFOLD

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 cm³	Area:	114.3135 cm²
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

```
M109 S200 ; wait for temperature to be reached
G90 ; 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
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
```

```
M109 S200 ; wait for temperature to be reached
G90 ; 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
```

STL (vertexes)

g-code (printing instructions)

3D model

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...
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)
Loaded Gecko_Headphone_v1.2a_Extruded_Scaled.stl

Cura

Cura - 14.07
Basic
Advanced
Plugins
Start/End-GCode
Machine
Nozzle size (mm) 0.4
Retraction
Speed (mm/s) 40.0
Distance (mm) 4.5
Quality
Initial layer thickness (mm) 0.3
Initial layer line with (%) 100
Cut off object bottom (mm) 0
Dual extrusion overlap (mm) 0.15
Speed
Travel speed (mm/s) 130
Bottom layer speed (mm/s) 30
Infill speed (mm/s) 0.0
Outer shell speed (mm/s) 0.0
Inner shell speed (mm/s) 0.0
Cool
Minimal layer time (sec) 5
Enable cooling fan
YM

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

CLEANING PROCESS

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

MADE
IN SPACE
NASA
PULL
Print Tray
P/N 03-0700-009
S/N F01
3DPRNT08M
S/N F01

Credit: NASA

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 **riscaldata** (~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

TREATMENT: REACTING POLYMER

AIRWOLF3D.COM

Resine epossidiche bi-componente

XTC-3D®

vapori di acetone

vapori di Acetato di Etile

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

http://artforcestudios.com/wp/design-services/

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.

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

DIRECTORS

E. CANESSA
(ICTP-SDU)

C. FONDA
(ICTP-SDU)

M. ZENNARO

An article on Nature

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

nature International weekly journal of science

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

NATURE | NEWS FEATURE

Science in three dimensions: The print revolution

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

Nicola Jones

04 July 2012

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

No Service 12:56 100%

THE PRINT REVOLUTION

BY NICOLA JONES

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

Christoph 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.

Printed models help to reveal how molecules function.

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.

22 | NATURE | VOL 487 | 5 JULY 2012

© 2012 Macmillan Publishers Limited. All rights reserved

56 100%

FEATURE NEWS

M. PONCE DE LEÓN C. ZOLLIKOFER/UNIV. ZURICH

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. Symes *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 Baveye, 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, Baveye 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 EDITORIAL P.6

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

5 JULY 2012 | VOL 487 | NATURE | 23

© 2012 Macmillan Publishers Limited. All rights reserved

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

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

NATURE.COM
To see a 3D printer in action, go to:
pa.nature.com/epidx

The Abdus Salam International Centre for Theoretical Physics

3D Printing Laboratory

The Abdus Salam International Centre for Theoretical Physics

3D Printing Laboratory

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

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

ICTP Science Dissemination Unit

A free and open book (and eBook):

sdu.ictp.it/3D

Table of Contents:

- 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
- Trabecular Bone Modeling with Support of 3D Printing of Physical Replicas
- Using 3D Printers at School: the Experience of 3drucken.ch
- Prehistoric Collections and 3D Printing for Education
- 3D Printing in Art Installations
- From Math to Jewel: an Example
- 3D Printing in the Developing World: Learning from Techfortrade's 3D4D Challenge
- 3D Printed Anatomic Replicas for Medical and Educational Purposes in Dental Surgery: Practical Projects from a Sustainable Development Point of View
- Perpetual Plastic Project

sdu.ictp.it/3D

Translations to other languages:

Italian

Spanish

Korean

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

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

K3DSurf v0.6.2: Math for Fun

Project OpenGL Config POV-Ray PageView About

IsoSurface | Parametric | Tools | Hall | ND

Parametric (OpenGL ON) | IsoSurface (OpenGL ON)

Cartesian Coordinates: F(x,y,z,t, ...) = 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 +
```

Examples (51)

CloseIso_2

Edit | Load

Delete

Clear | Newin

Compute

-4	X	4
-4	Y	4
-4	Z	4

Activate the condition CND {x,y,z,t} :

Options: (Export/Resolution/Optimisation)

Drawing Options

Lines Triangles Fill Infos Axe Norm

Cut Grid

XYZ X Y Z

Grid Resolution

X Y Z xyz

Animation/Morph:

Anim(Rotation) Morph (use "t")

K3DSurf v0.5.5 : Math for Fun
Basic
Options
Pov
Export
ND
Hall
Tools
Iso
Parametric Surface
IsoSurface
POV-Ray: test
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^
Y
X
Z
IsoWindow

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

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[1], 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

- `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, sub_a, sub_b, ...}]` imports a subelement.
- `Import["file.stl", {{elem_1, elem_2, ...}}]` 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", {expr_1, expr_2, ...}, {{elem_1, elem_2, ...}}]` treats each $expr_i$ as specifying the corresponding $elem_i$.
- `Export["file.stl", expr, opt_1 -> val_1, ...]` exports *expr* with the specified option elements taken to have the specified values.
- `Export["file.stl", {elem_1 -> expr_1, elem_2 -> expr_2, ...}, "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]
```

Ultimaker

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
Carlo Fonda, ICTP Scientific Fablab