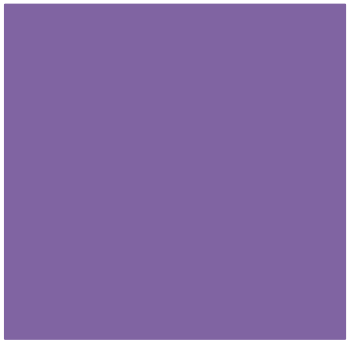


Fused deposition Modelling

carmelo.demaria@centropiaggio.unipi.it

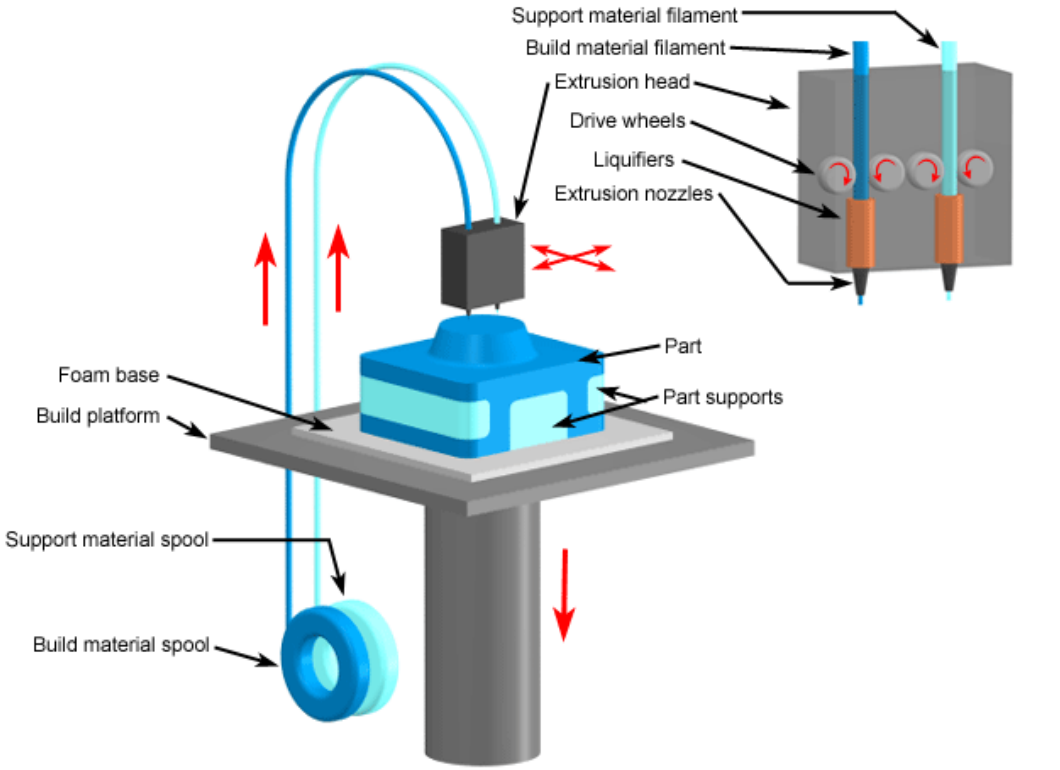
Fused deposition modelling (FDM)

- FDM is the second most widely used AM technology, after stereolithography.
- A plastic filament is unwound from a coil and supplies material to an extrusion nozzle. The nozzle is heated to melt the plastic and has a mechanism which allows the flow of the melted plastic to be turned on and off.
- The nozzle is mounted to a mechanical stage which can be moved in both horizontal and vertical directions.
- As the nozzle is moved over the table in the required geometry, it deposits a thin bead of extruded plastic to form each layer.
- The plastic hardens immediately after being squirted from the nozzle and bonds to the layer below. The entire system is contained within a chamber which is held at a temperature just below the melting point of the plastic.

Fused deposition modelling (FDM)

https://www.youtube.com/watch?v=WHO6G67GJbM

Fused deposition modelling



With basics of polymer rheology

MATERIALS FOR FDM

Materials

- FFF = Fused Filament Fabrication
- Filament: fine diameter plastic that exits from an extruder (some may refer to the plastic feed stock as filament as well)
- Typically, the diameter of the filament varies between 1 mm and 3mm
- The standard extruder produces filament using high pressure and heat to force molten plastic through a very tiny hole.

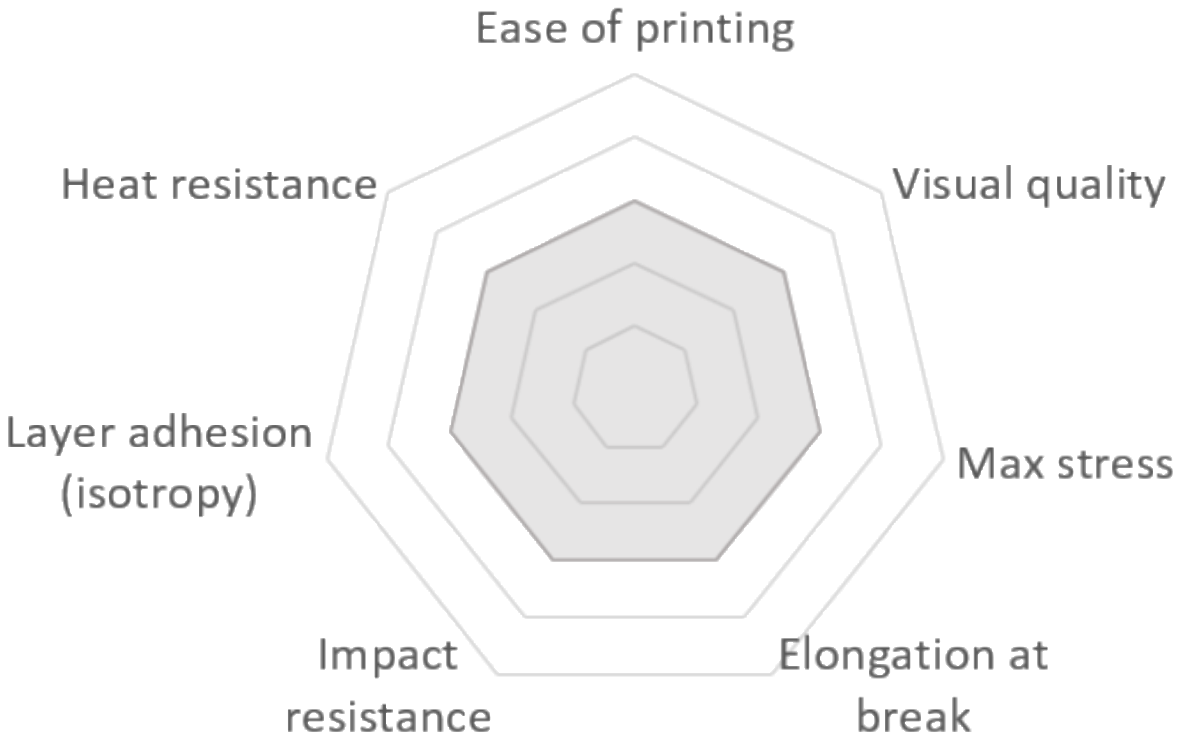
Materials

- "Standard" materials:
  - Poly-Lactic-Acid (PLA) (soft and hard)
  - Acrylonitril-Butadiene-Stiren (ABS)
  - Nylon
  - Polycarbonate (PC)
  - Poly vinyl alcohol (PVA)
  - Thermoplastic polyurethane (TPU)
  - Polyethylene Terephthalate Glycol (PETG)
  - Conductive (carbon and graphen loaded materials)
  - Metallic loaded plastics

https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared

Choosing the right FDM material

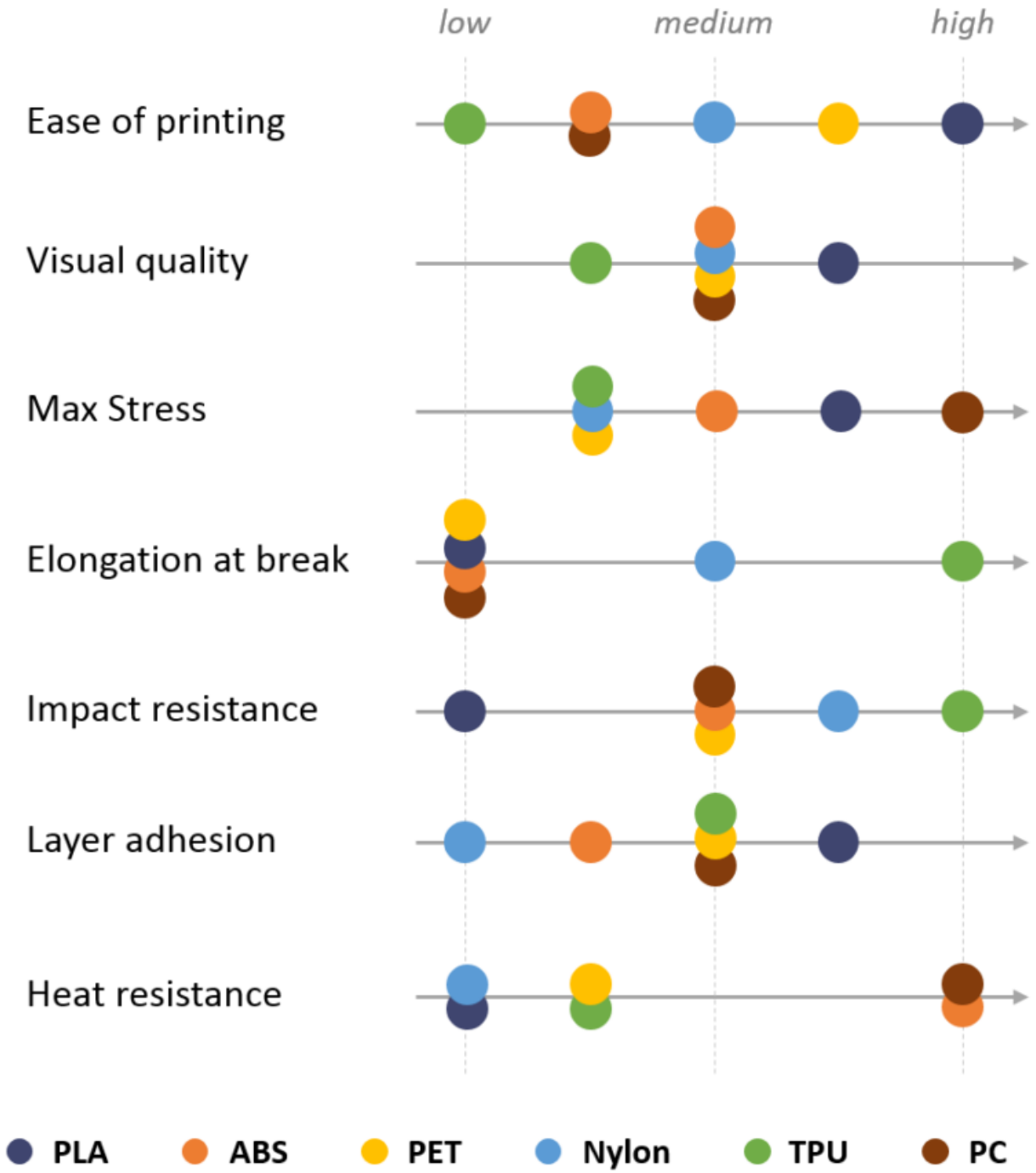
For a given application



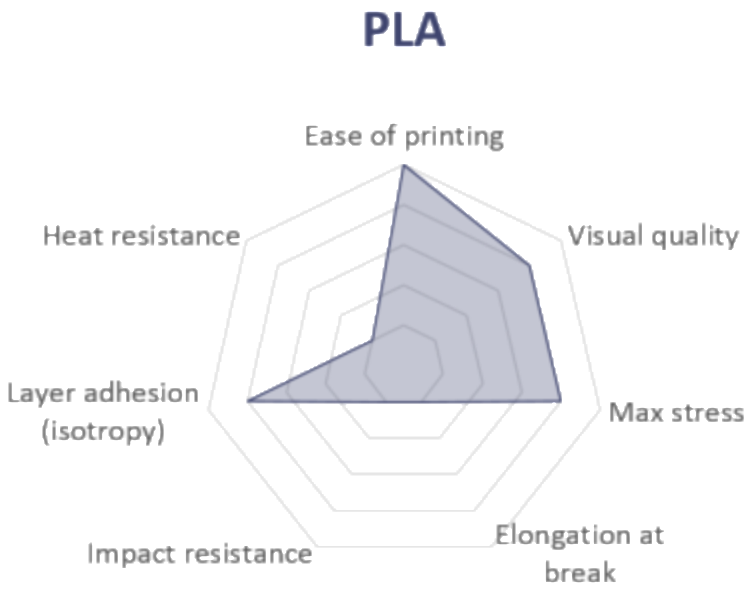
Other side properties: humidity resistance, toxicity [1]

[1]: Azimi et al, Emissions of Ultrafine Particles and Volatile Organic Compounds from Commercially Available Desktop Three-Dimensional Printers with Multiple Filaments, Environmental Science & Technology, 2016

Choosing the right FDM material



Polylactic acid

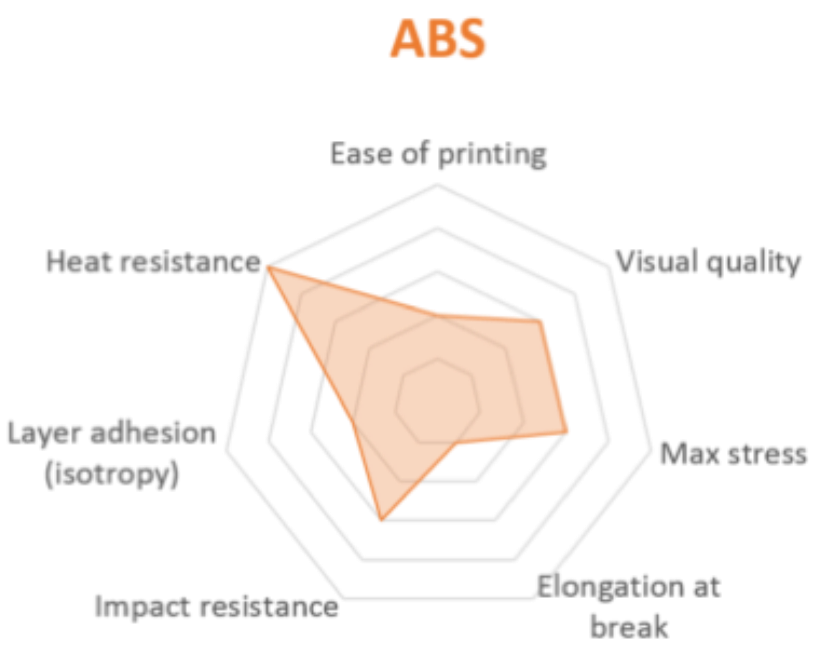


Nozzle Temp (°C)	**200-220**
Bed Temp (°C)	**60**

Pros	**Cons**
Biosourced, biodegradable	Low humidity resistance
Odorless	Can't be glued easily
Can be post-processed with sanding paper and painted with acrylics	
Good UV resistance	

PLA is the easiest polymer to print and provides good visual quality.
It is very rigid and actually quite strong, but is very brittle.

Acrylonitril-Butadiene-Stiren

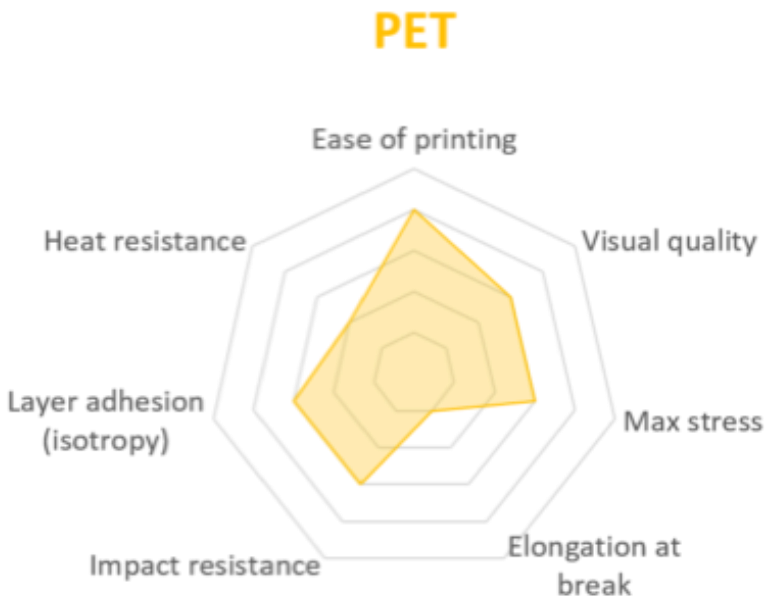


Nozzle Temp (°C)	**230-250**
Bed Temp (°C)	**80**

Pros	**Cons**
Can be post-processed with acetone vapors for a glossy finish	UV sensitive
Can be post-processed with sanding paper and painted with acrylics	Odor when printing
Acetone can also be used as strong glue	Potentially high fume emissions
Good abrasion resistance	

ABS is usually picked over PLA when higher temperature resistance and higher toughness is required.

Polyethylene Terephthalate Glycol

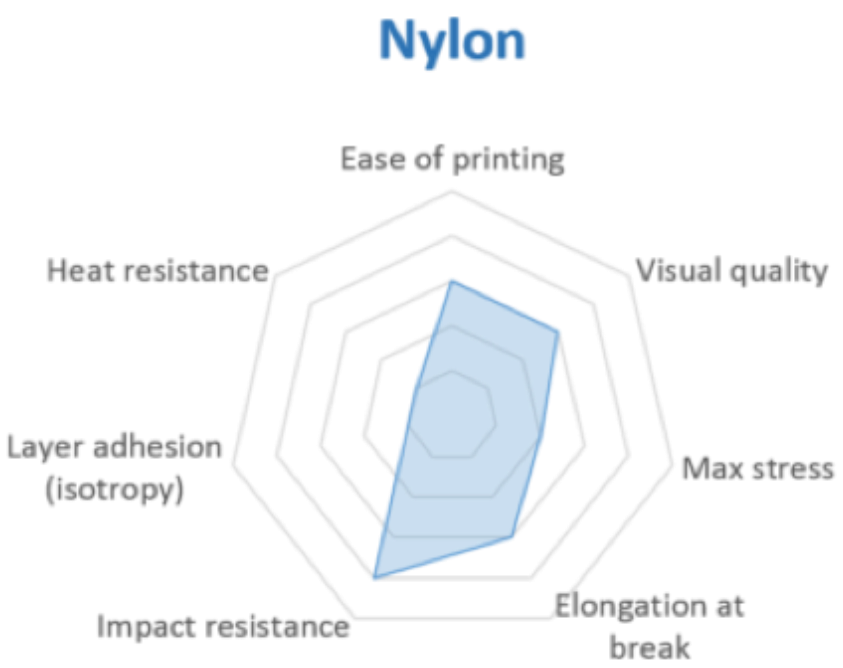


Nozzle Temp (°C)	**230-250**
Bed Temp (°C)	**80**

Pros	**Cons**
Can come in contact with foods	Heavier than PLA and ABS
High humidity resistance	
High chemical resistance	
Recyclable	
Good abrasion resitance	
Can be post-processes with sanding paper and painted with acrylics	

PET is a slightly softer polymer that is well rounded and possesses interesting additional properties with few major drawbacks.

Nylon 6

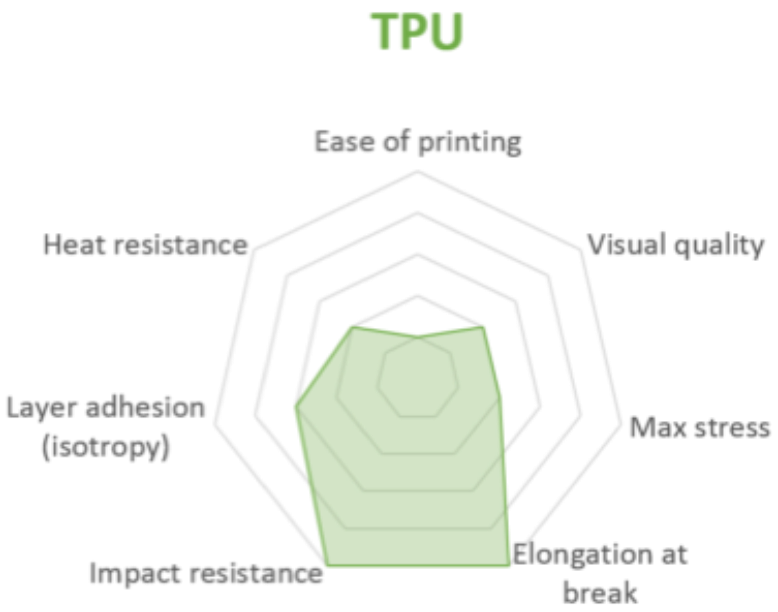


Nozzle Temp (°C)	**235 - 245**
Bed Temp (°C)	**60**

Pros	**Cons**
Good chemical resistance	Absorbs moisture
High strength	Potentially high fume emissions

Nylon possesses great mechanical properties, and in particular, the best impact resistance for a non-flexible filament. Layer adhesion can be an issue, however.

Thermoplastic polyurethane 95A

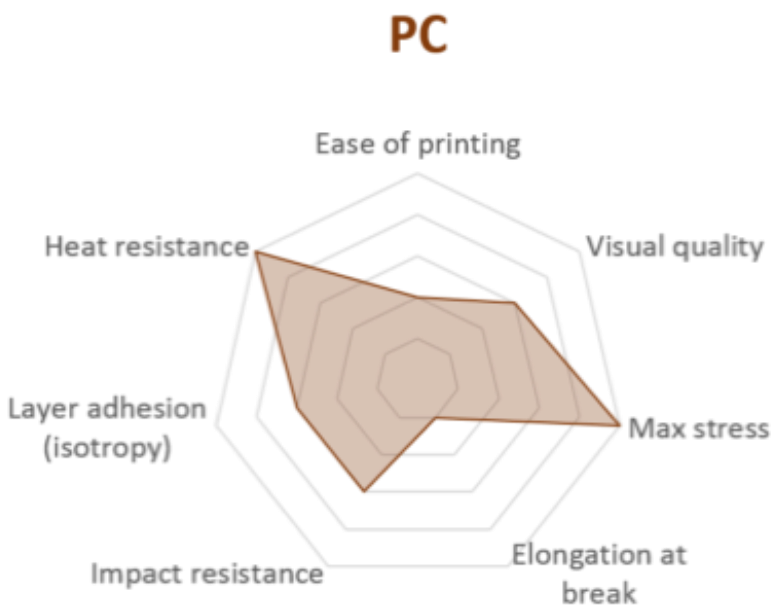


Nozzle Temp (°C)	**225 - 235**
Bed Temp (°C)	**0**

Pros	**Cons**
Good abrasion resistance	Difficult to post process
Good resistance to oil and grease	Can't be glued easily

TPU is mostly used for flexible applications, but its very high impact resistance can open for other applications.

Polycarbonate (PC)

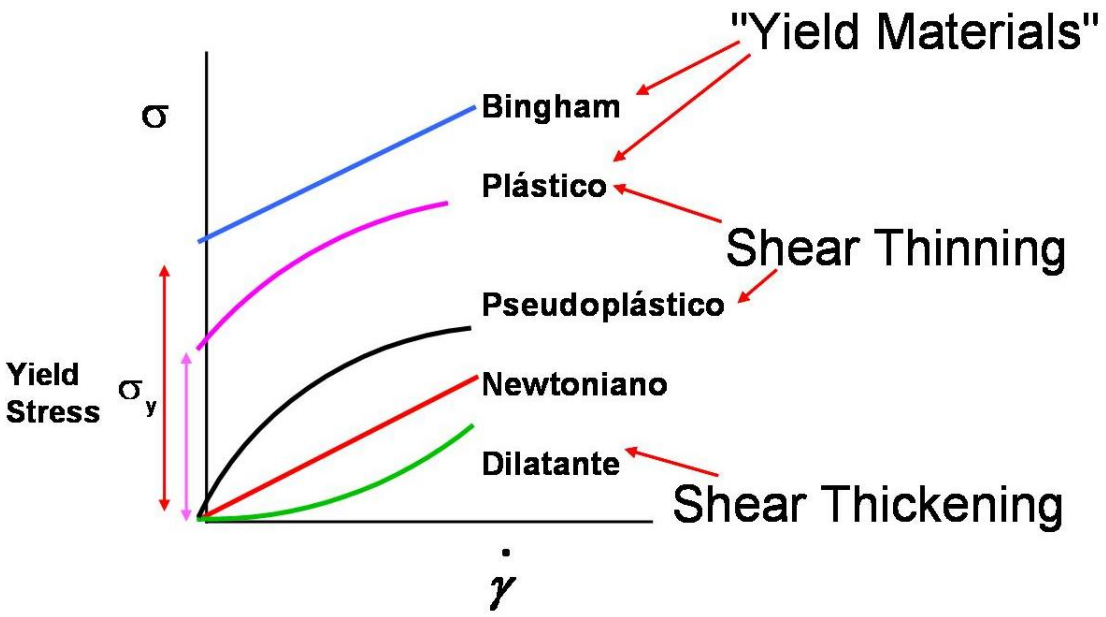


Nozzle Temp (°C)	**250 - 270**
Bed Temp (°C)	**80**

Pros	**Cons**
Can be sterilized	UV sensitive
Easy to post-process (sanding)	

PC is the strongest material of all, and can be an interesting alternative to ABS as the properties are quite similar.

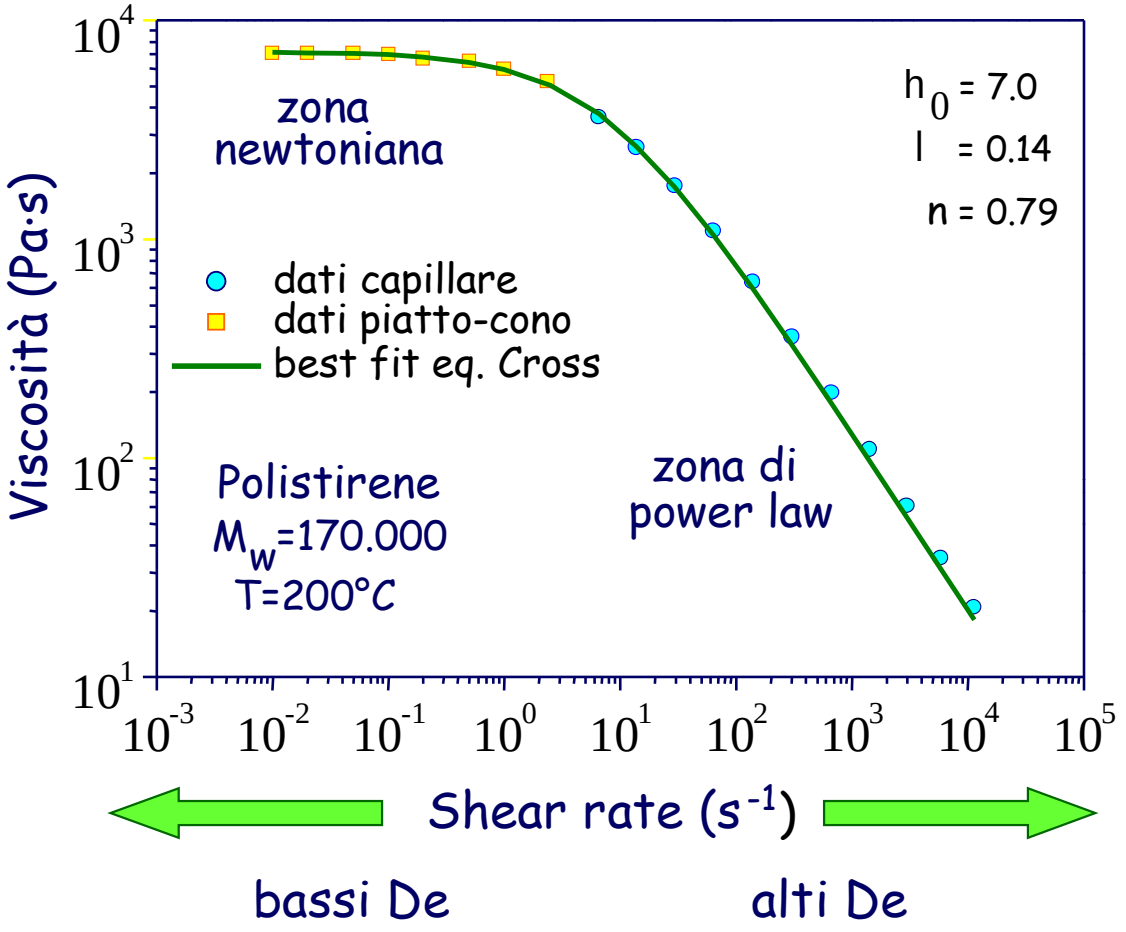
Rheology


"Yield Materials"
σ
Bingham
Plástico
Shear Thinning
Pseudoplástico
Yield Stress
σy
Newtoniano
Dilatante
Shear Thickening
γ̇

Variabili che influenzano la reologia dei polimeri

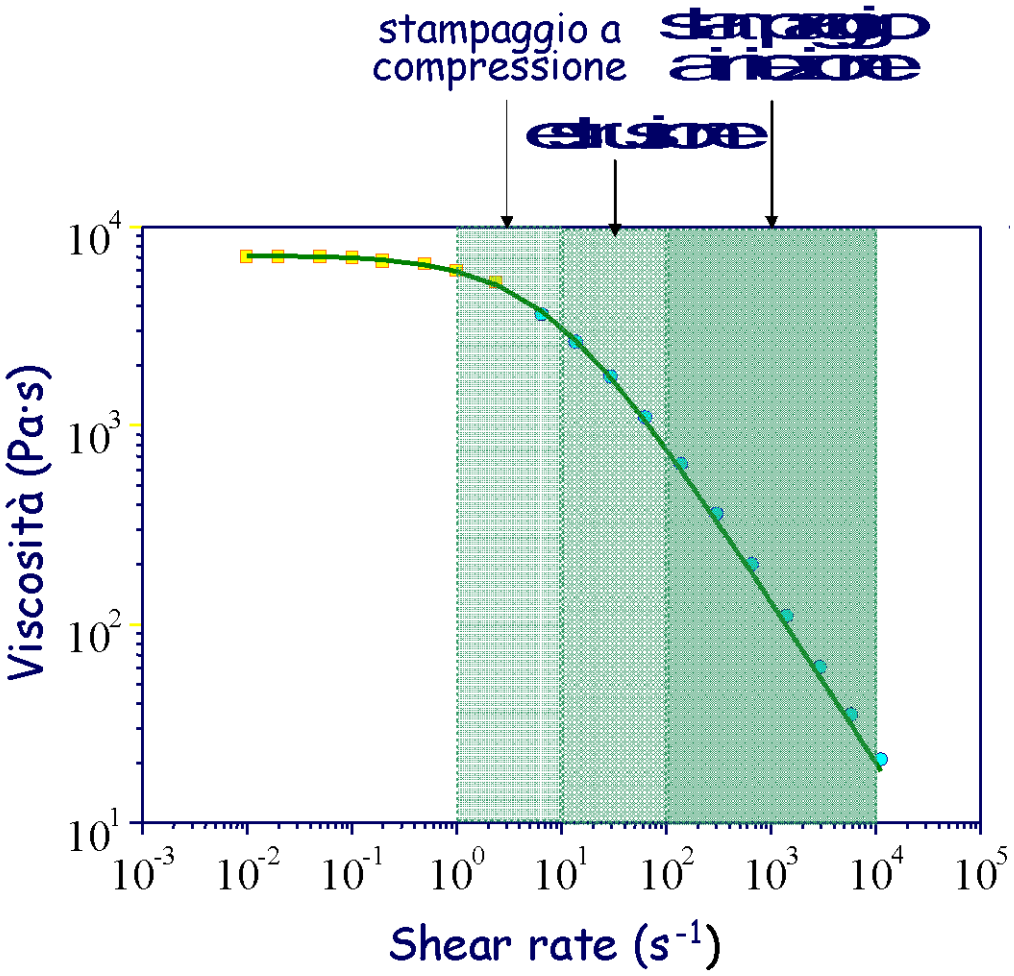
- Variabili reologiche:
  - deformazione
  - velocità di deformazione
- Variabili strutturali-compositive:
  - peso molecolare medio
  - polidispersità (Mw/Mn)
  - architettura molecolare (es: presenza di ramificazioni)
  - presenza di una fase dispersa (quantità, dimensionale media e distribuzione, forma)
  - contenuto di additivi (es: plastificanti)
- Variabili termodinamiche:
  - pressione
  - temperatura

Curva di flusso (viscosità in regime stazionario): comportamento shear thinning

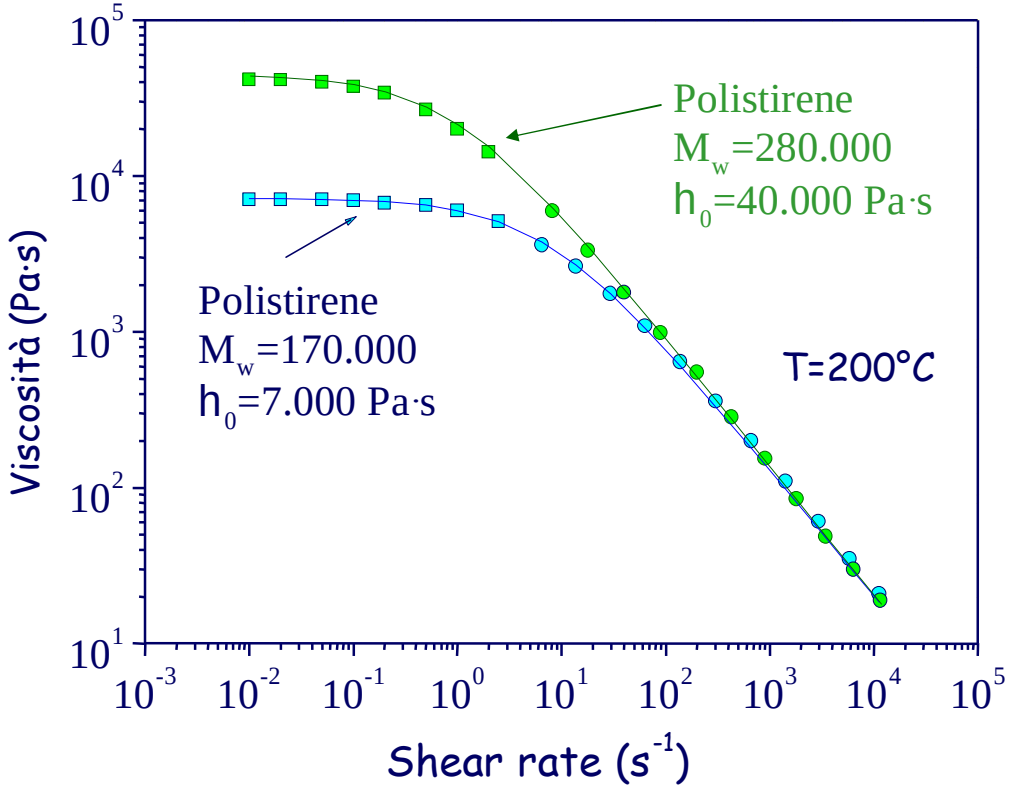


$$\eta = \frac{\eta_0}{1+(\lambda\dot{\gamma})^n}$$

Viscosità e condizioni tipiche di processo



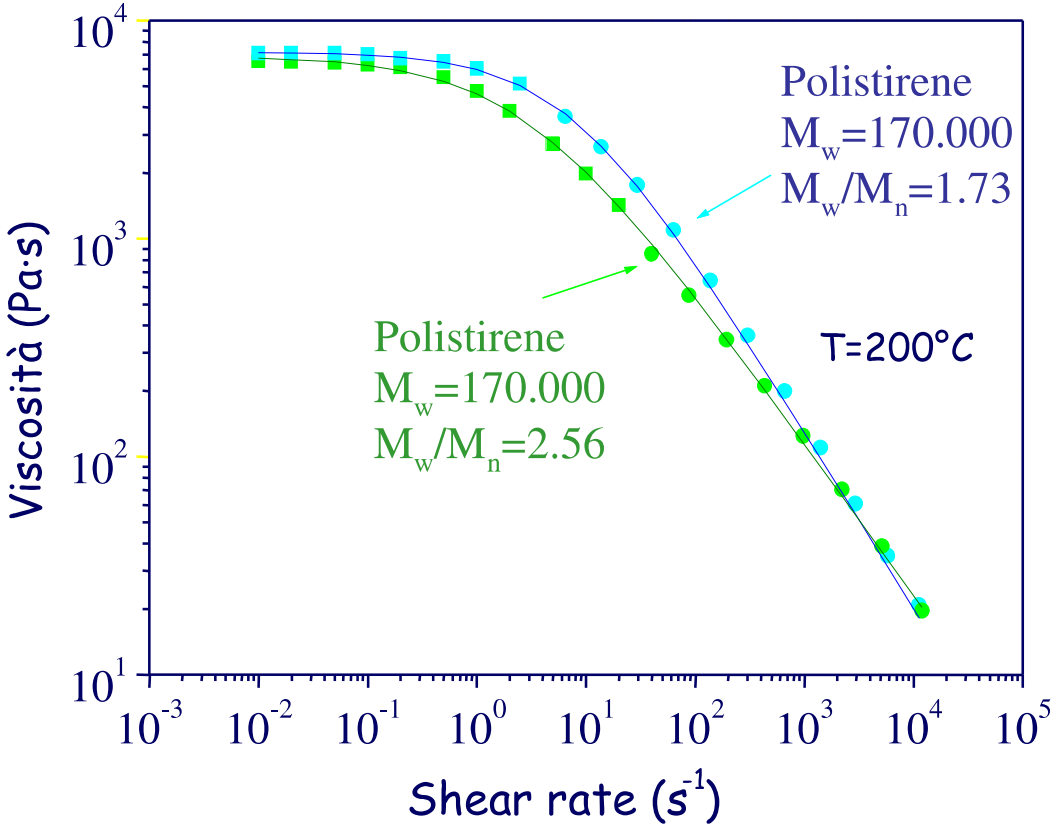
Effetto del peso molecolare



Una caratteristica distintiva dei polimeri ad alto peso molecolare:

$$h_0 \mu M_w^{3.4}$$

Effetto della polidispersità



Maggiore è la polidispersità e più larga è la curva di viscosità

Indice di polidispersione

Da Wikipedia, l'enciclopedia libera.

L'**indice di polidispersione** è una misura dell'uniformità di distribuzione dei pesi molecolari in un determinato polimero. La **polidispersità** viene espressa tramite un indice calcolato dal rapporto tra la massa molare media ponderale e la massa molare media numerica del polimero, essendo:

- *massa molare media numerica*: $M_n = \sum n_i M_i / \sum n_i$
- *massa molare media ponderale*: $M_w = \sum w_i M_i / \sum w_i = \sum n_i M_i^2 / \sum n_i M_i$

in cui:

- M_i = massa molecolare dell'i-esima molecola;
- n_i = numero di moli delle molecole aventi massa molecolare pari a M_i;
- w_i = massa delle molecole con massa molecolare pari a *i*.

Siccome la massa molare media ponderale è sempre maggiore della massa molare media numerica, l'indice di polidispersività (essendo pari al rapporto M_w/M_n) assume sempre valori maggiori di 1.

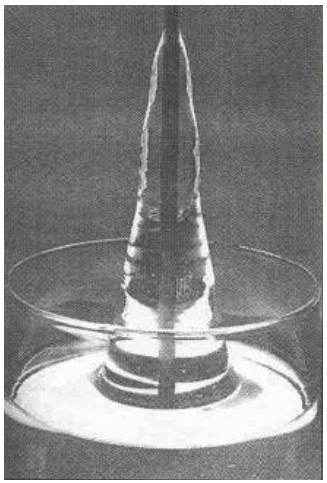
Il termine "monodisperso" viene per convenzione utilizzato fino a valori di indice di polidispersività minore a 1,1.[1] In caso contrario il polimero è detto "polidisperso".

Nel caso di polimeri ottenuti tramite polimerizzazione a stadi si hanno valori dell'indice di polidispersione più bassi (intorno a 2), mentre nel caso di polimeri ottenuti tramite polimerizzazione a catena si hanno valori di polidispersione più elevati.

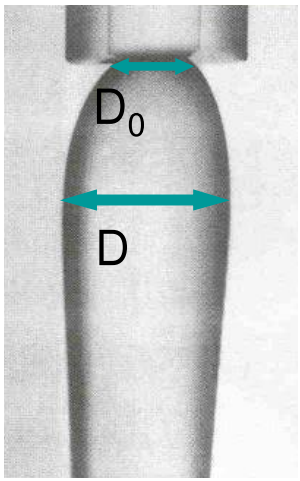
Fenomeni dovuti all'elasticità del fuso

le componenti elastiche sono legate agli sforzi normali

rod climbing

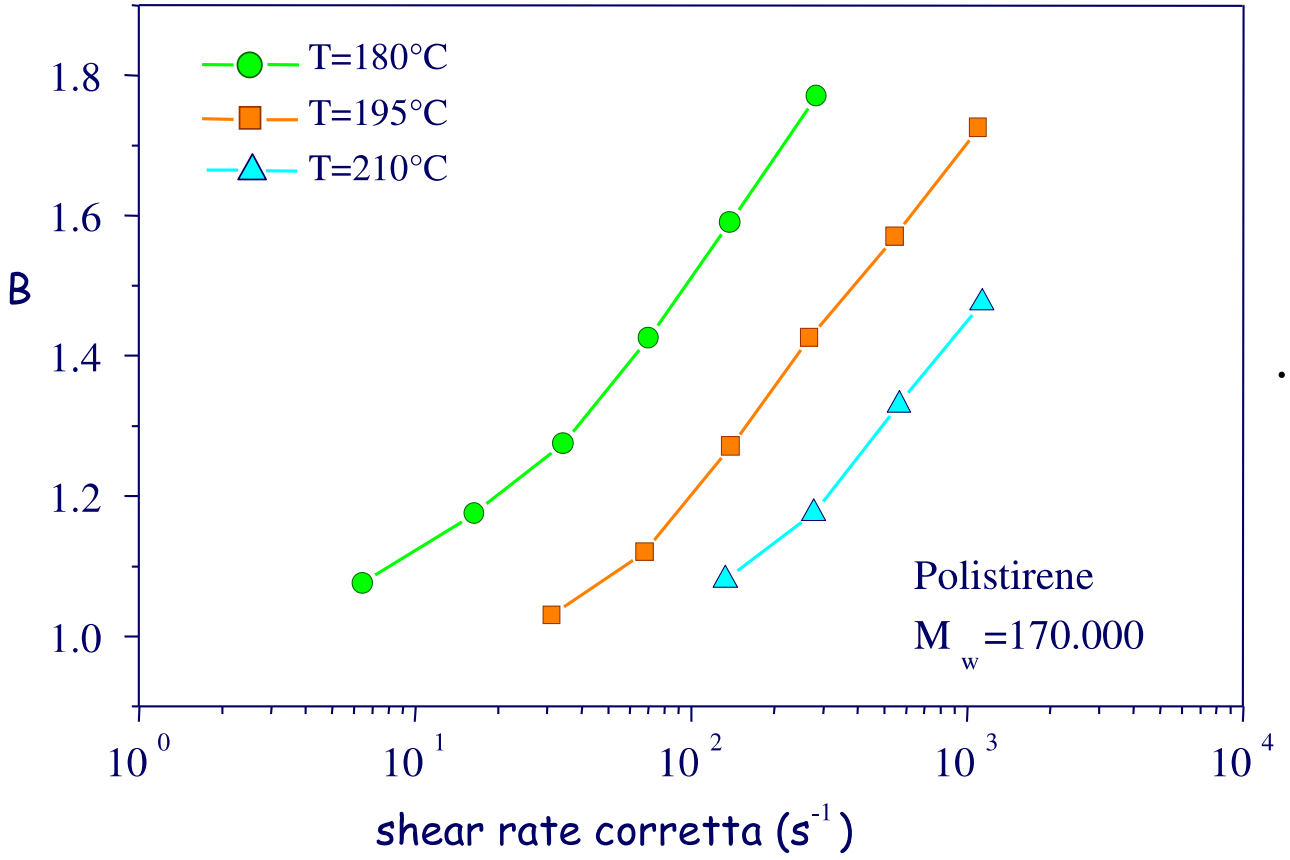


die swell

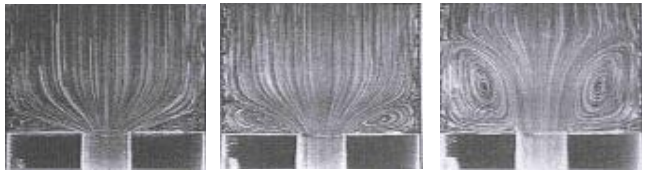


$$B = \frac{D}{D_0}$$

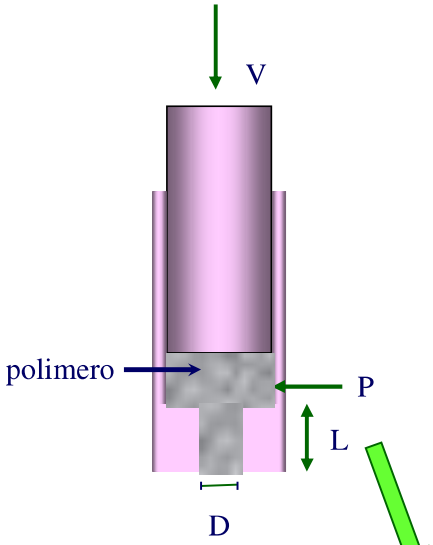
Il die swell del polistirene



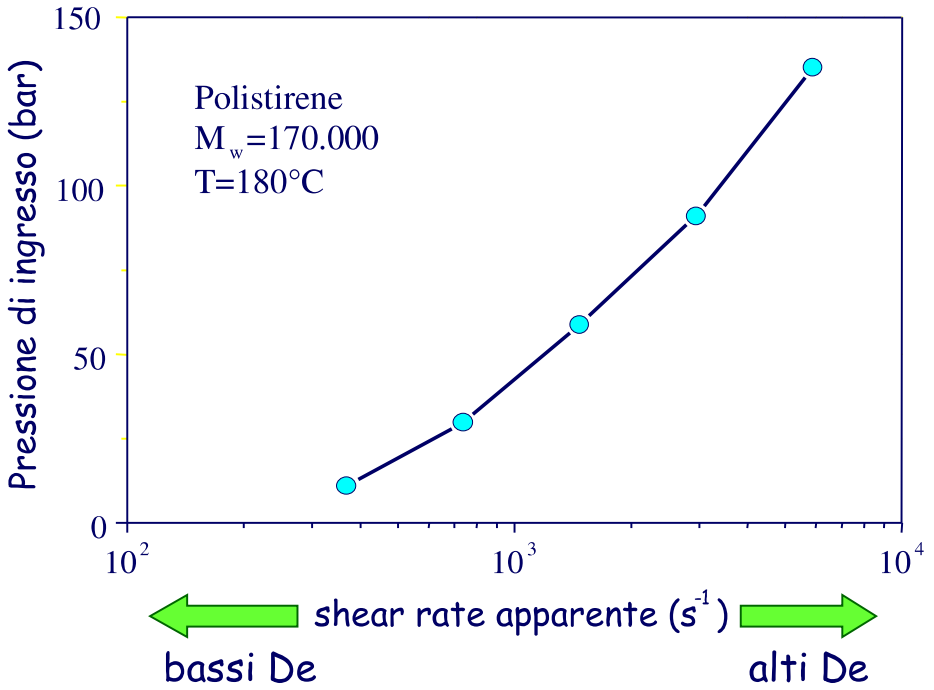
Altra manifestazione dell'elasticità del fuso: la pressione di ingresso



shear rate crescente

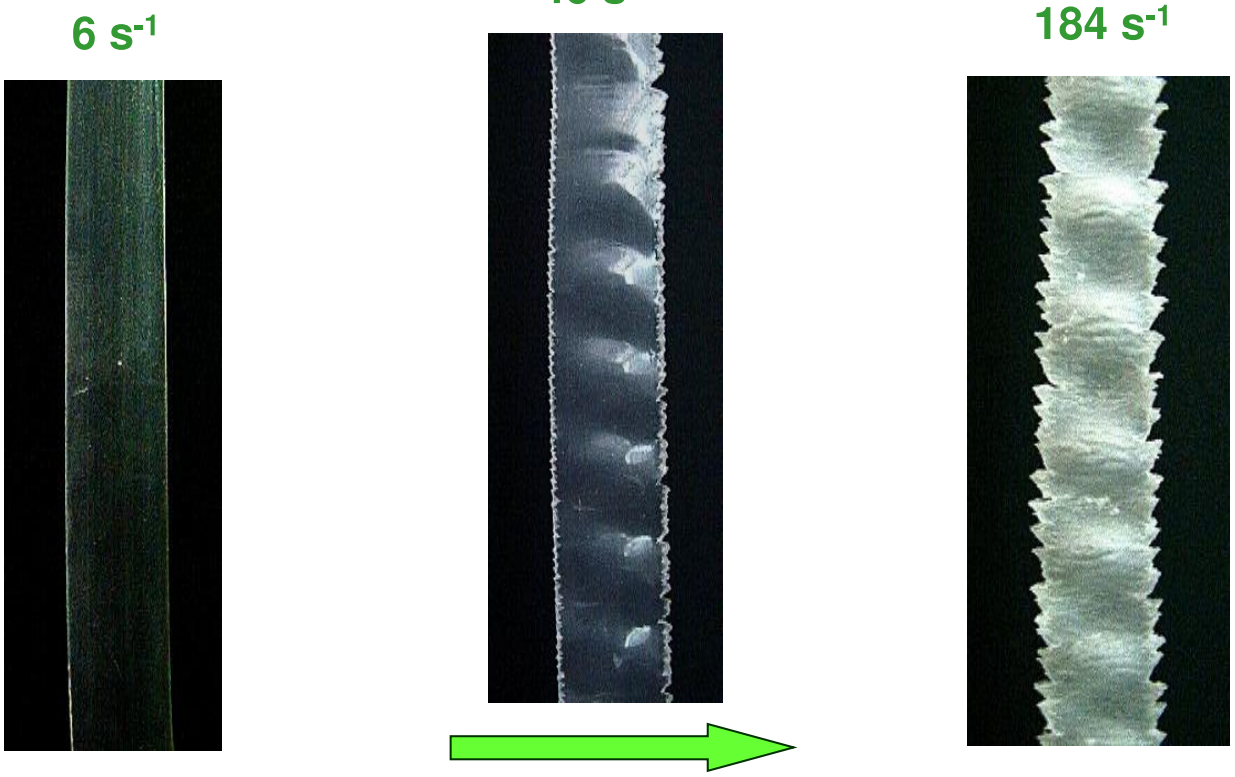


$$P = P_{ing} + P_{visc}$$



La melt fracture aumenta all'aumentare della shear rate

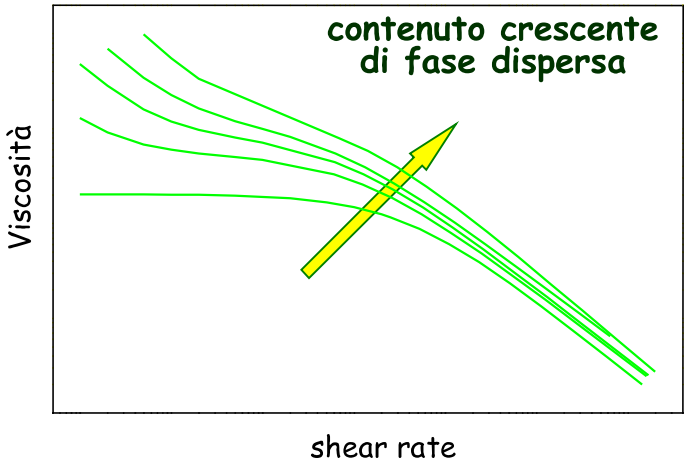
copolimero SIS a 120°C



Comportamento reologico di sistemi polimerici multifasici

- Alcuni tipi di sistemi multifase:
  - polimeri rinforzati con cariche minerali o fibre
  - polimeri tenacizzati con fase gommosa dispersa
  - blend immiscibili
  - copolimeri a blocchi
  - schiume
- Variabili che influenzano la reologia di sistemi multifase:
  - Quantità di fase dispersa
  - media e distribuzione delle dimensioni particelle
  - fattore di forma delle particelle
  - distanza inter-particellare media
  - deformabilità della fase dispersa

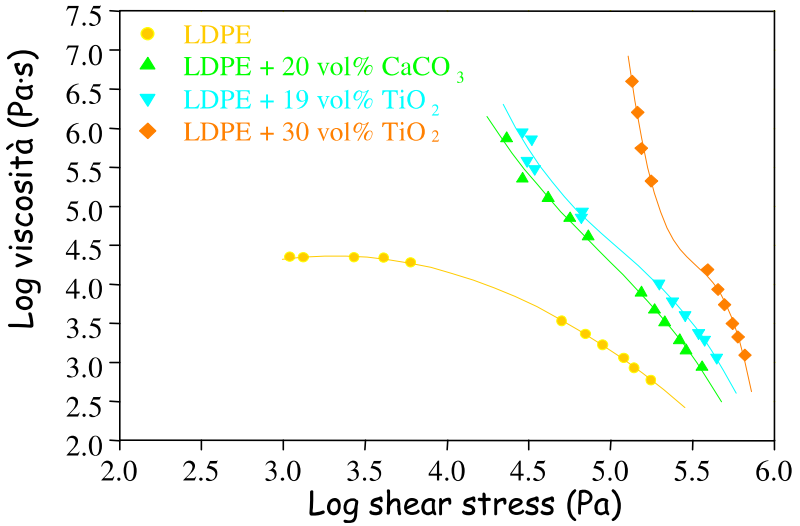
Un importante effetto della fase dispersa: lo yield stress



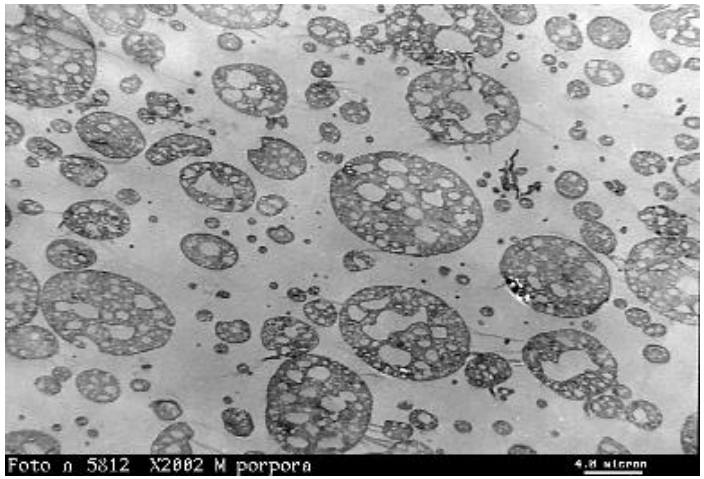
a basse shear rate scompare il plateau newtoniano

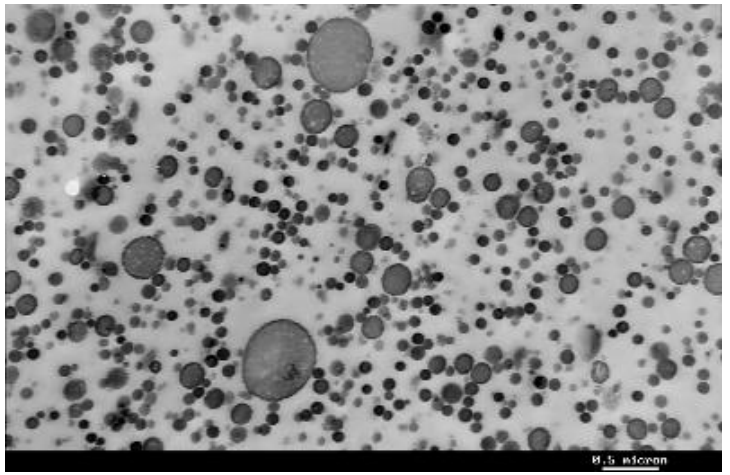
C.Y. Ma, J.L. White, F.C. Weissert, K. Min, *SPE Tech. Papers*,31 (1985)

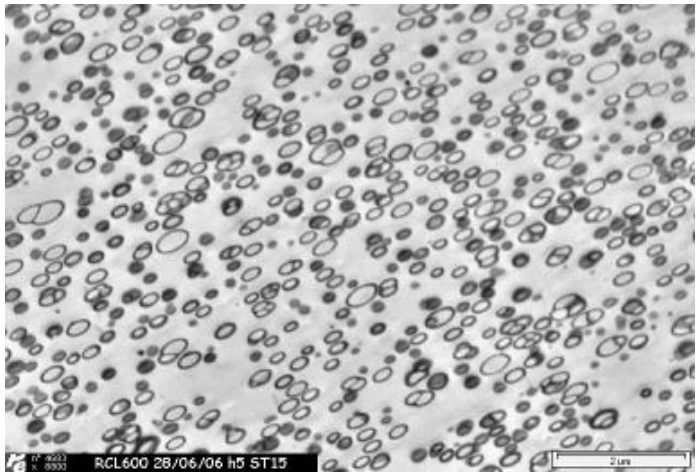
la presenza di yield stress è meglio evidenziata in un grafico viscosità-sforzo

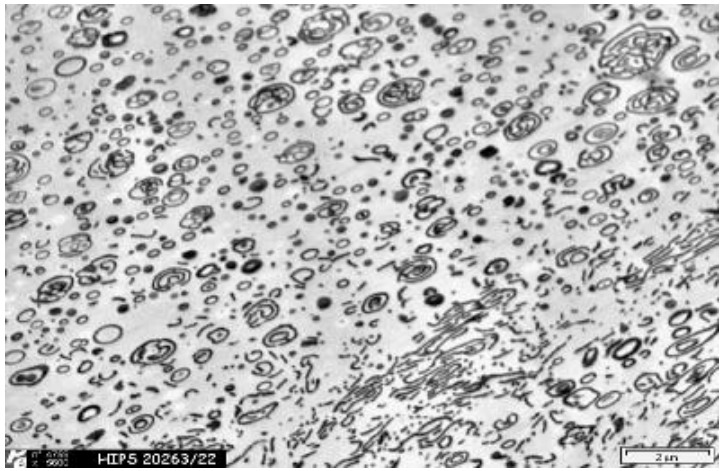


polimeri con fase gommosa (reticolata) dispersa









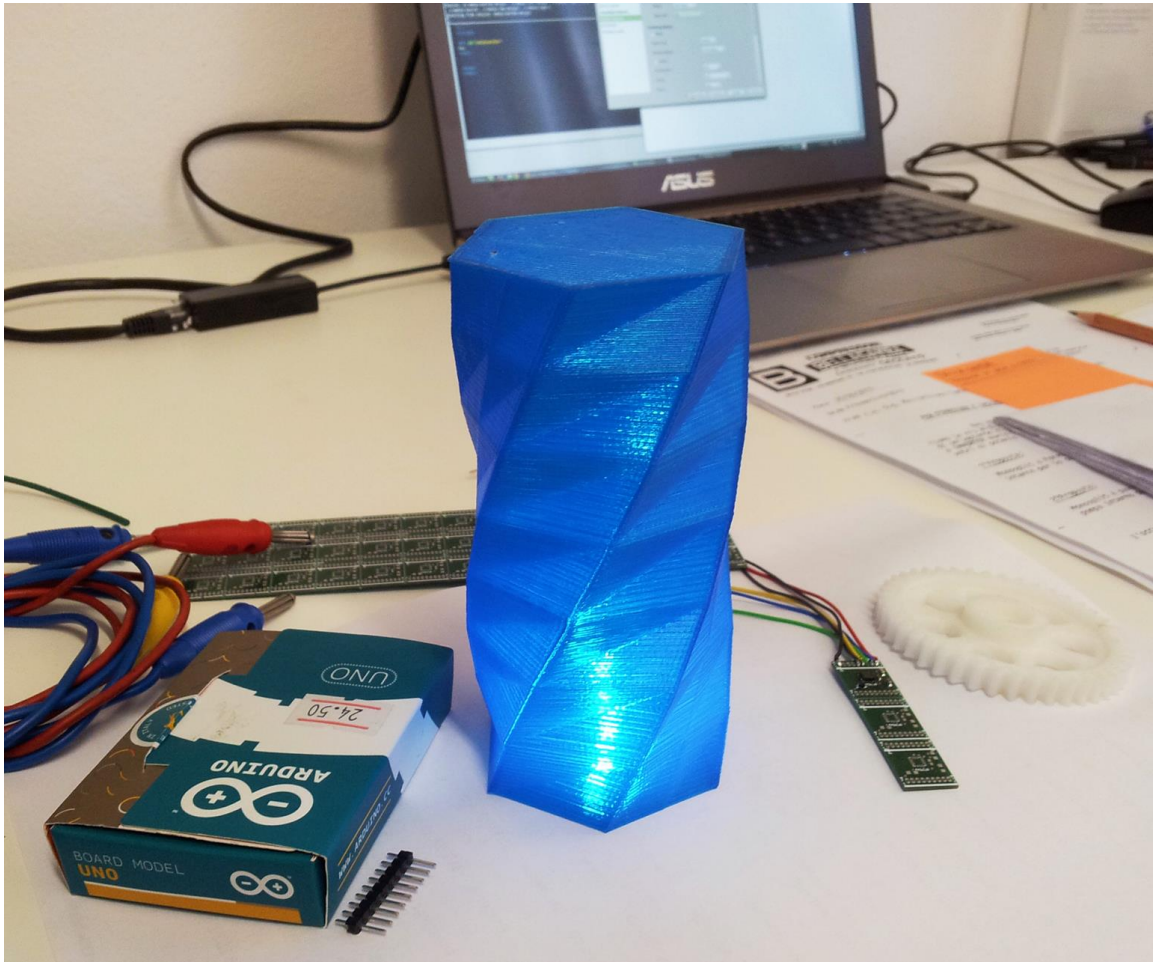
The Rep Rap Project

OPEN 3D PRINTING

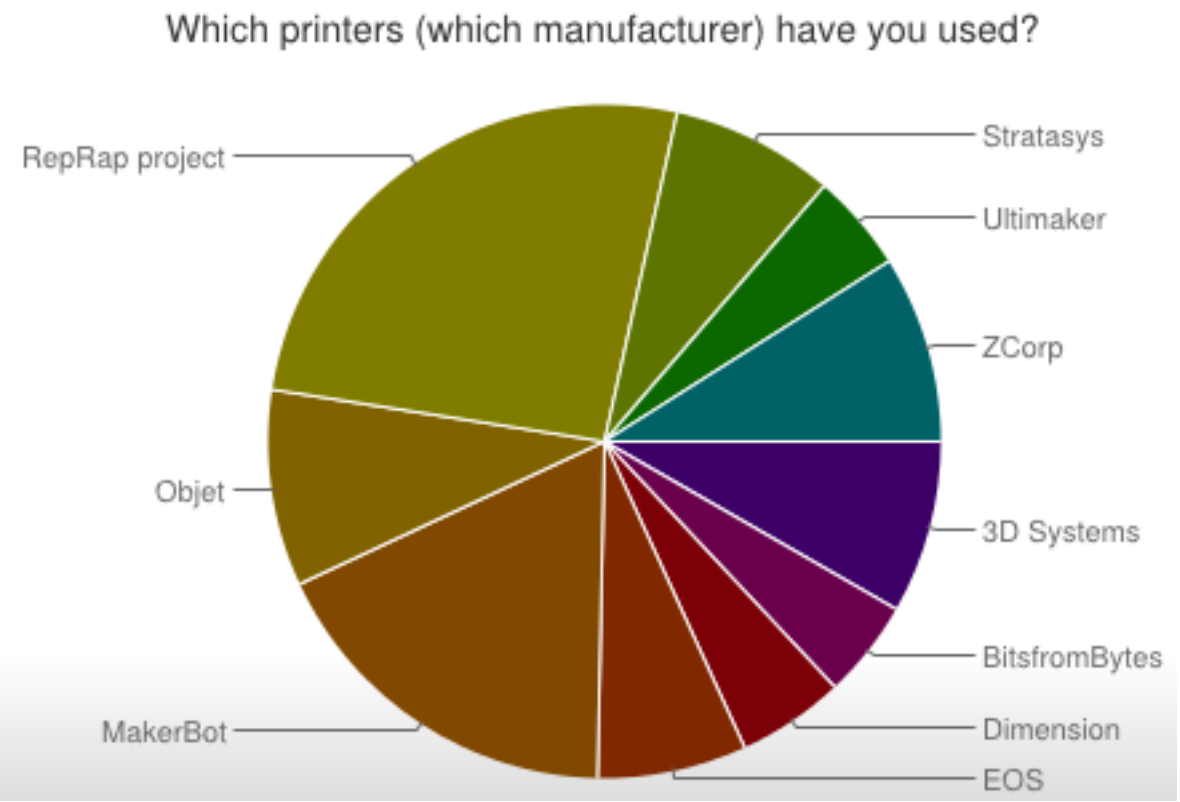
Open 3D printing: the RepRap project

- RepRap is first general-purpose self-replicating manufacturing machine.
- RepRap takes the form of a free desktop 3D printer capable of printing plastic objects.
- Since many parts of RepRap are made from plastic and RepRap prints those parts, RepRap self-replicates by making a kit of itself - a kit that anyone can assemble given time and materials.

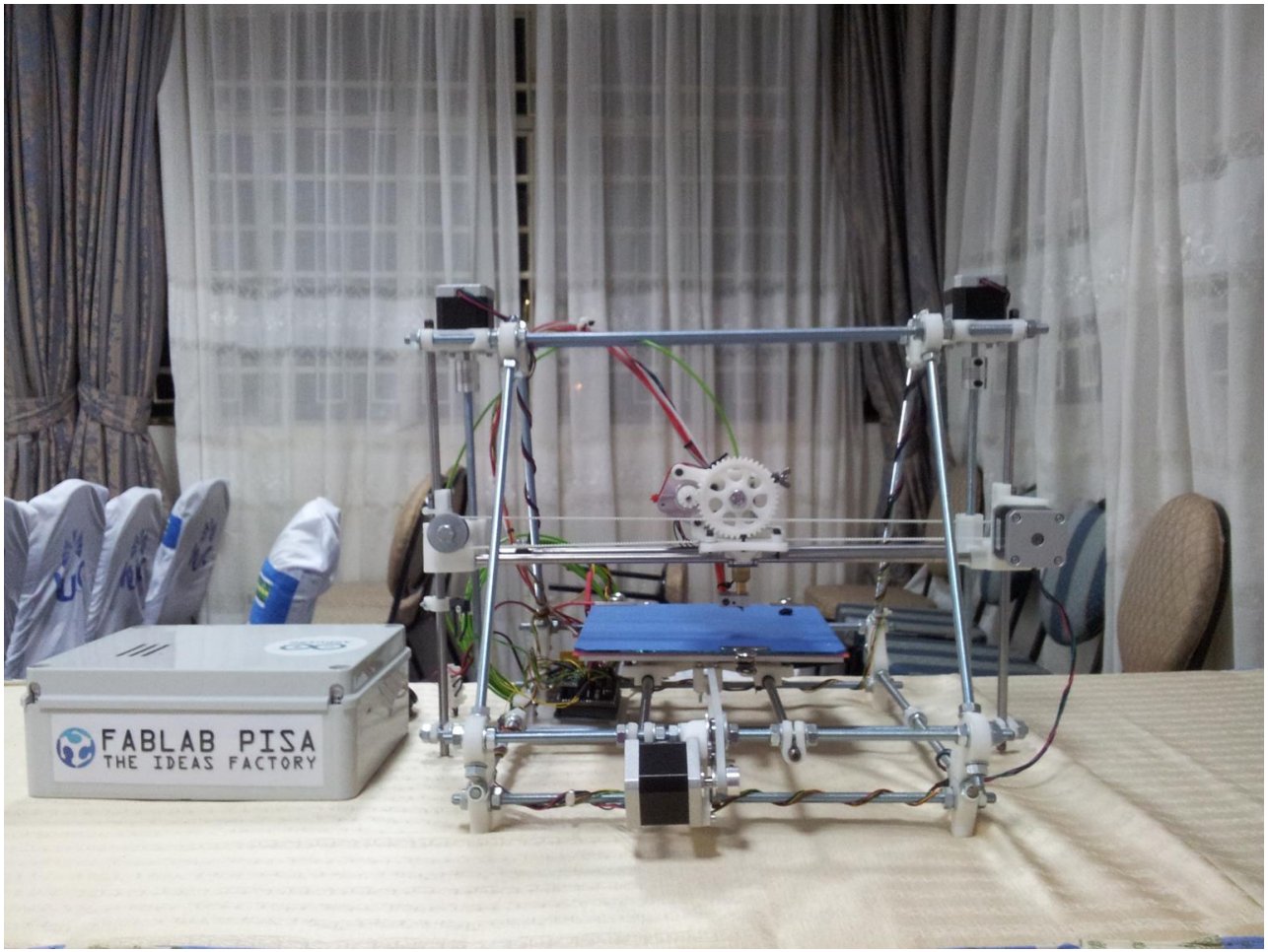
The RepRap Project



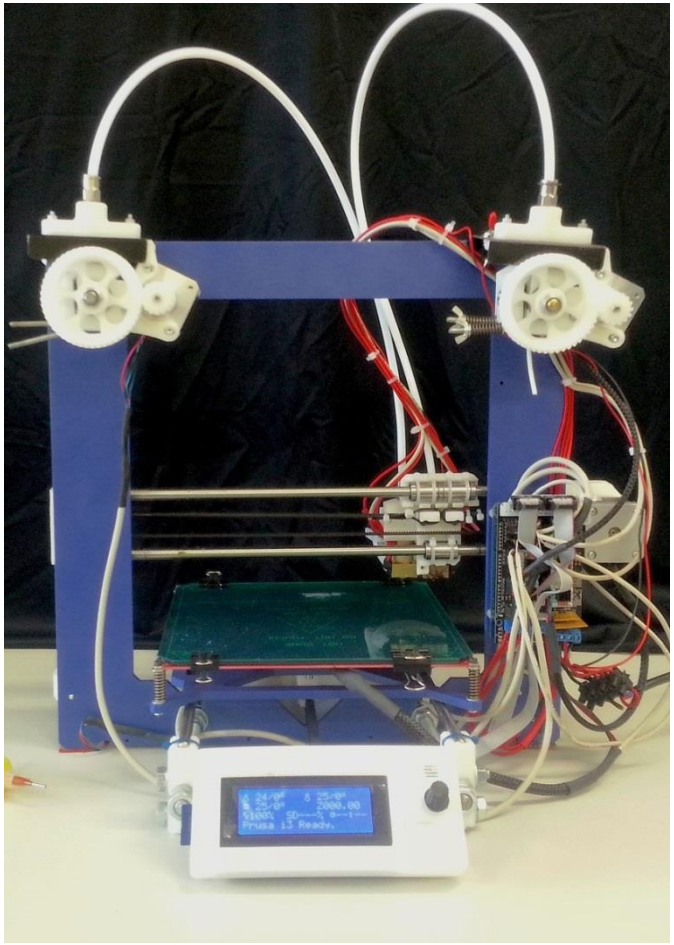
The RepRap Project



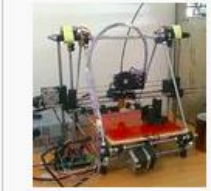
The RepRap Project



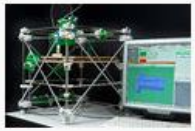
The RepRap Project



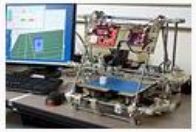
How many RepRaps?



Prusa (*license: GPL*)



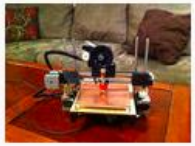
Darwin (*license: GPL*)



Mendel (*license: GPL*)

Huxley (*license: GPL*)

RepRap Morgan (*license: GPL*)



Printrbot (*license: CC-BY-SA*)

Cartesio (*license: CC-BY-SA*)

RepRapPro Mendel (*license: GPL*)

RepRapPro Huxley (*license: GPL*)

Eventorbot (*license: CC-BY-SA*)

3drag (*license: CC-BY-SA*)

Prusa i3 Rework Introduction (*license: GPL*)

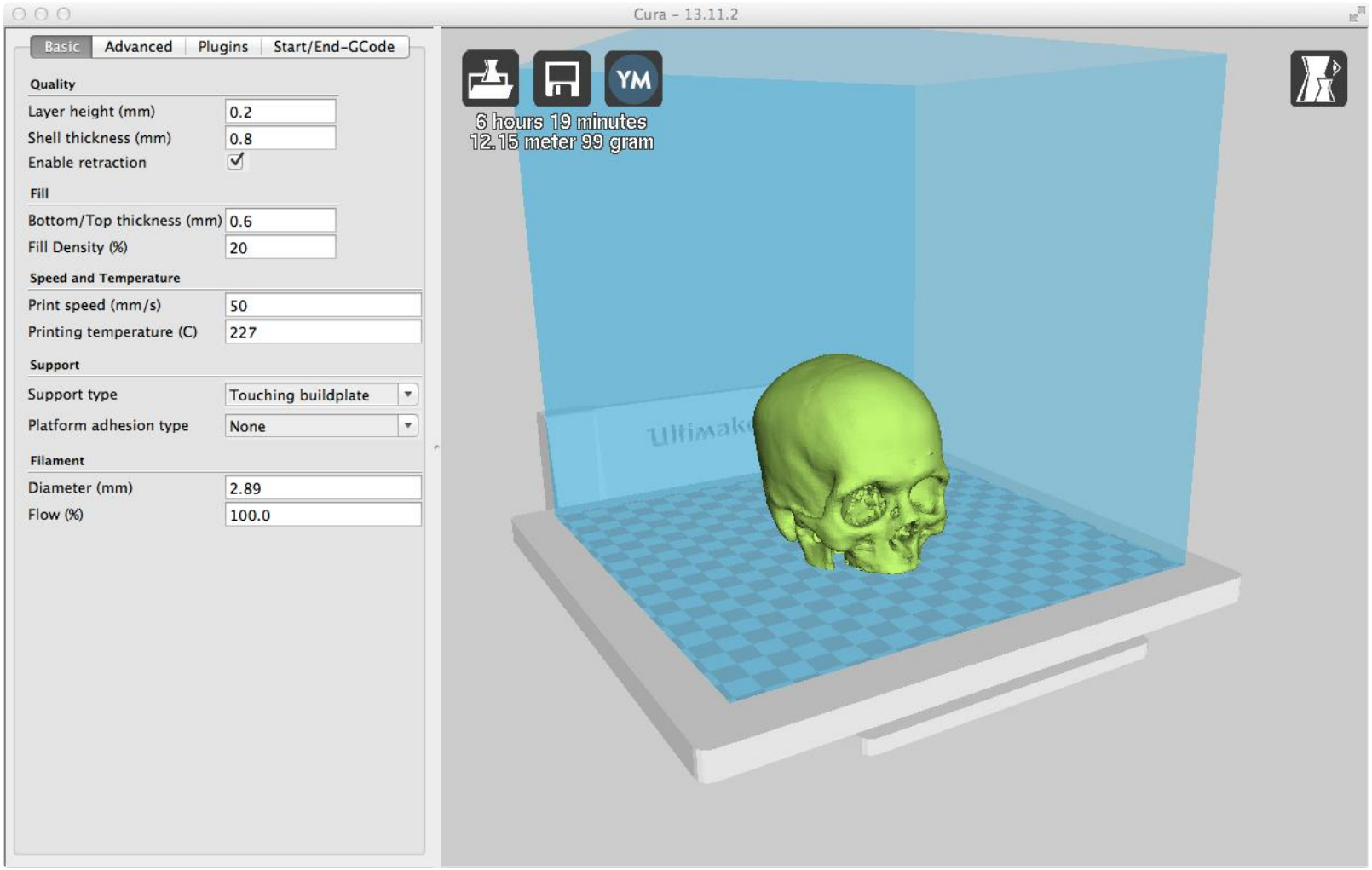
Open question

- Which are the Intellectual Property Implications of Low-Cost 3D Printing?

- Is the Open Source 3-D printing an enabling technology for self-directed sustainable development?

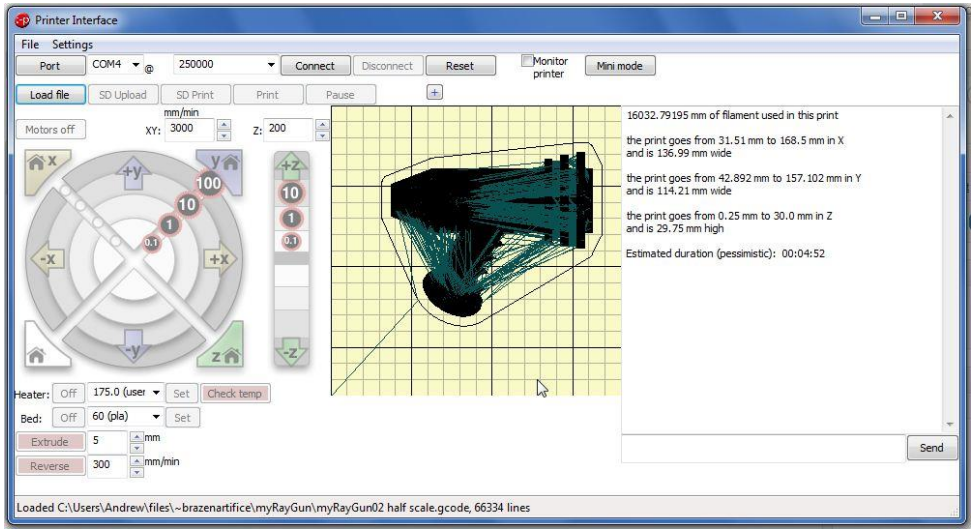
A LOOK INTO SLICING PARAMETERS

Cura

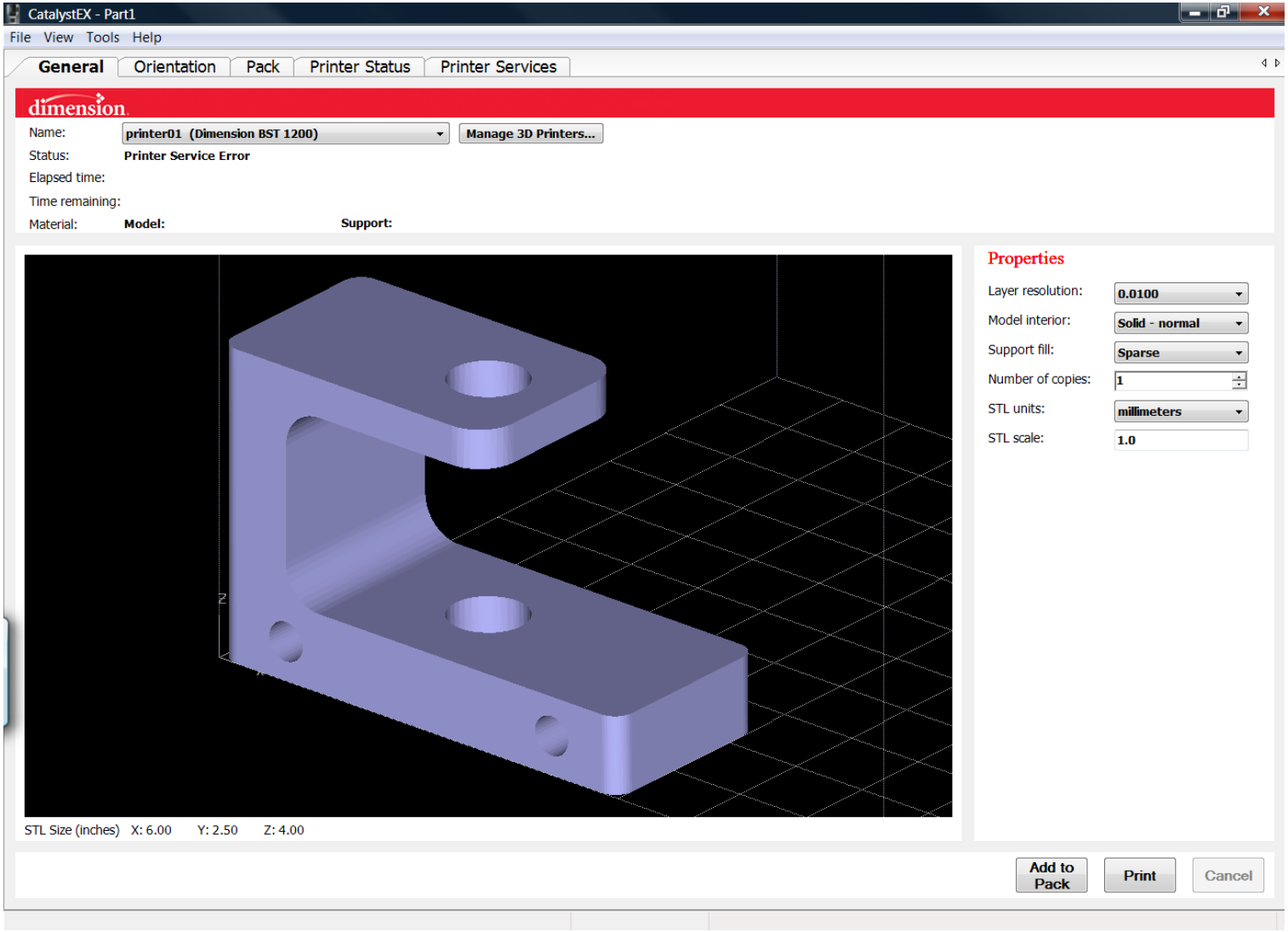

Cura – 13.11.2
Basic
Advanced
Plugins
Start/End-GCode
Quality
Layer height (mm)
0.2
Shell thickness (mm)
0.8
Enable retraction
Fill
Bottom/Top thickness (mm)
0.6
Fill Density (%)
20
Speed and Temperature
Print speed (mm/s)
50
Printing temperature (C)
227
Support
Support type
Touching buildplate
Platform adhesion type
None
Filament
Diameter (mm)
2.89
Flow (%)
100.0
YM
6 hours 19 minutes
12.15 meter 99 gram

Slic3r

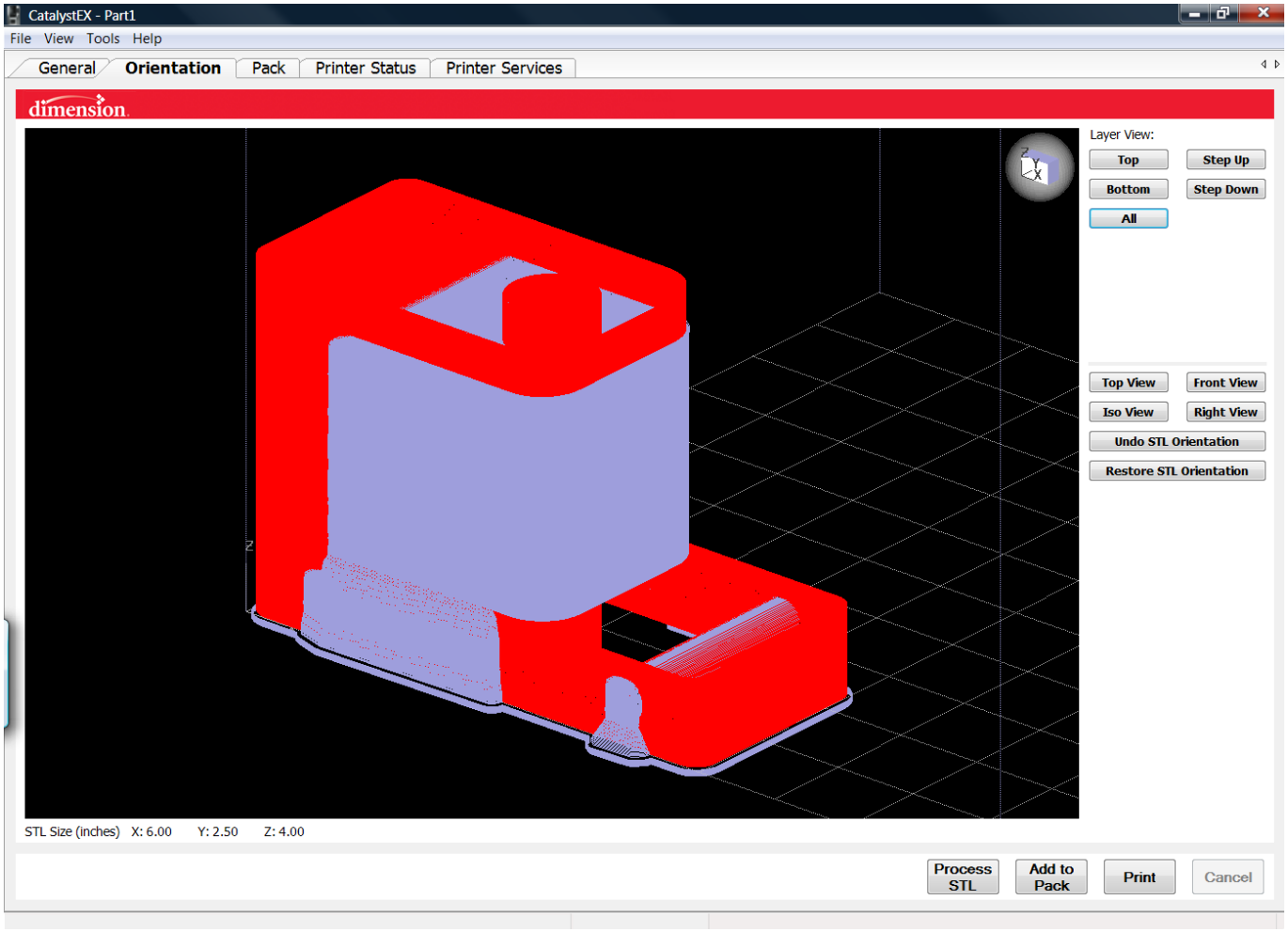

Slic3r
G-code generator for 3D printers
Slic3r
Plater
Print Settings
Filament Settings
Printer Settings
More
Less
45° ccw
45° cw
Rotate
Scale
Split
Name
Copies
Scale
40x10.STL
2
100%
coupling.stl
2
100%
Add...
Autoarrange
Export G-code
Delete
Delete All
Export STL...
Print settings:
- default -
Filament:
- default -
Printer:
- default -


Printer Interface
File
Settings
Port
COM4
@
250000
Connect
Disconnect
Reset
Monitor printer
Mini mode
Load file
SD Upload
SD Print
Print
Pause
mm/min
Motors off
XY:
3000
Z:
200
16032.79195 mm of filament used in this print
the print goes from 31.51 mm to 168.5 mm in X
and is 136.99 mm wide
the print goes from 42.892 mm to 157.102 mm in Y
and is 114.21 mm wide
the print goes from 0.25 mm to 30.0 mm in Z
and is 29.75 mm high
Estimated duration (pessimistic): 00:04:52
Heater:
Off
175.0 (user
Set
Check temp
Bed:
Off
60 (pla)
Set
Extrude
5
mm
Reverse
300
mm/min
Send
Loaded C:\Users\Andrew\files\~brazenartifice\myRayGun\myRayGun02 half scale.gcode, 66334 lines

Stratasys Catalyst

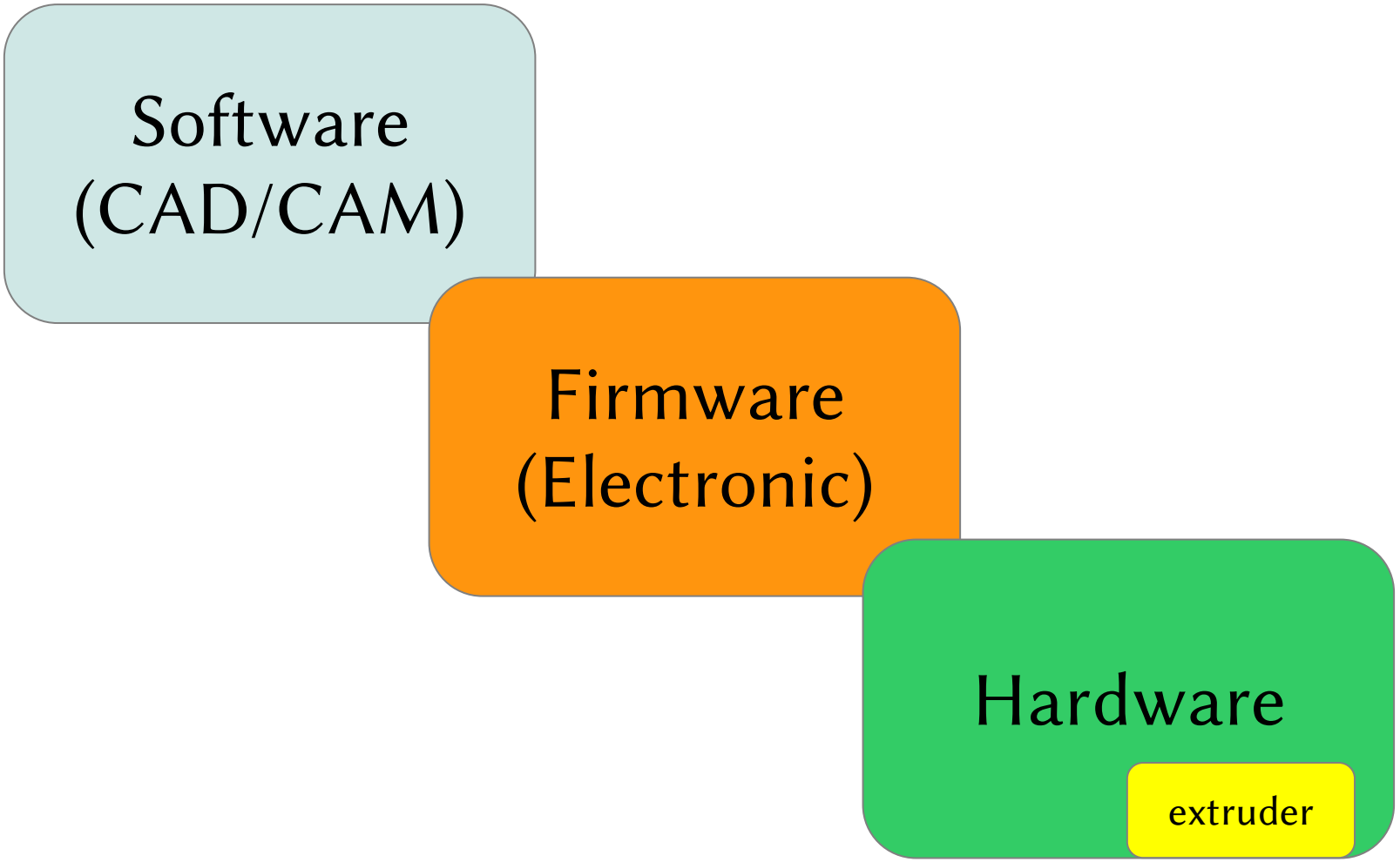


Stratasys Catalyst



ANATOMY OF A 3D PRINTING SYSTEM

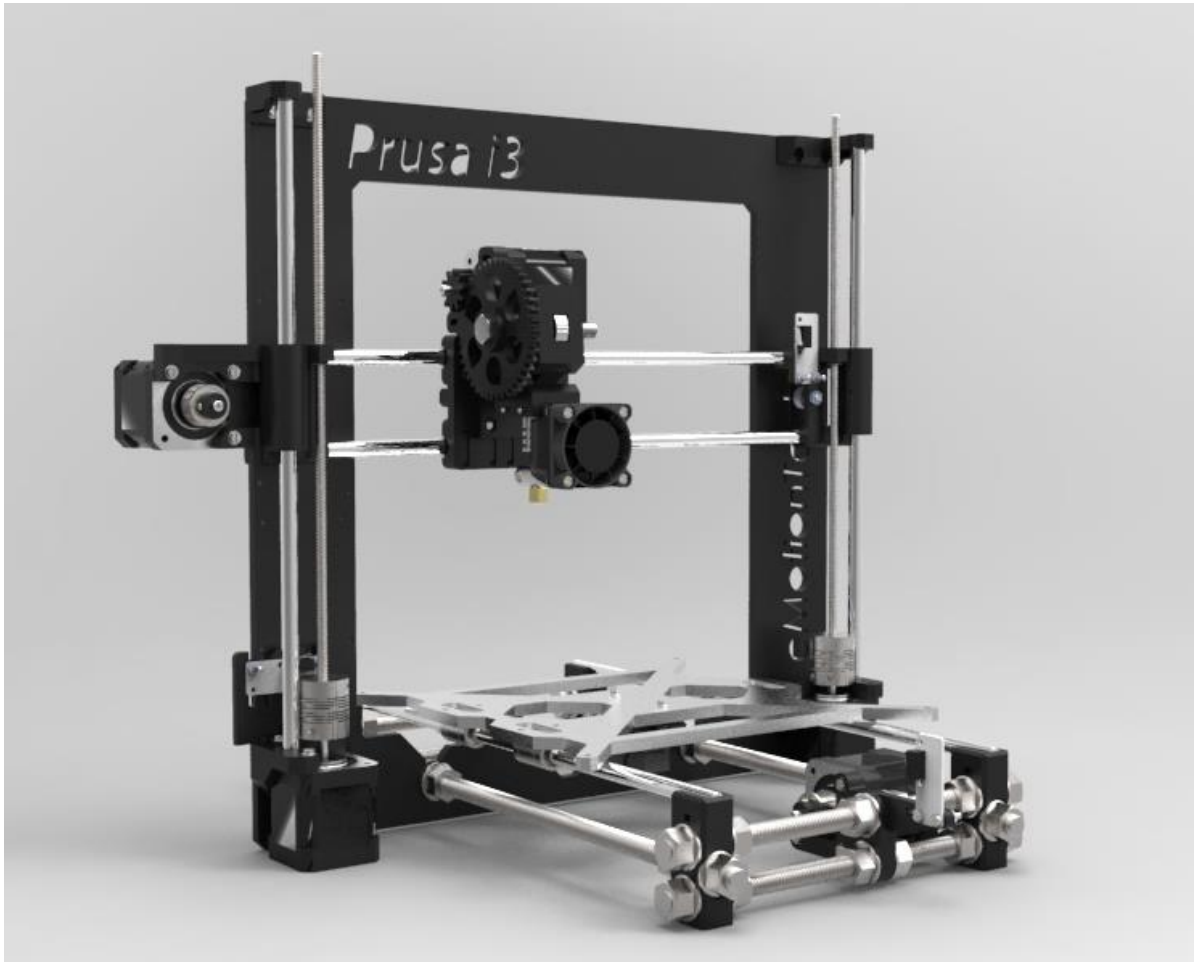
Main components of a 3D printer system



Case study

THE PRUSA I3 REWORK

Mechanical structure



Hardware

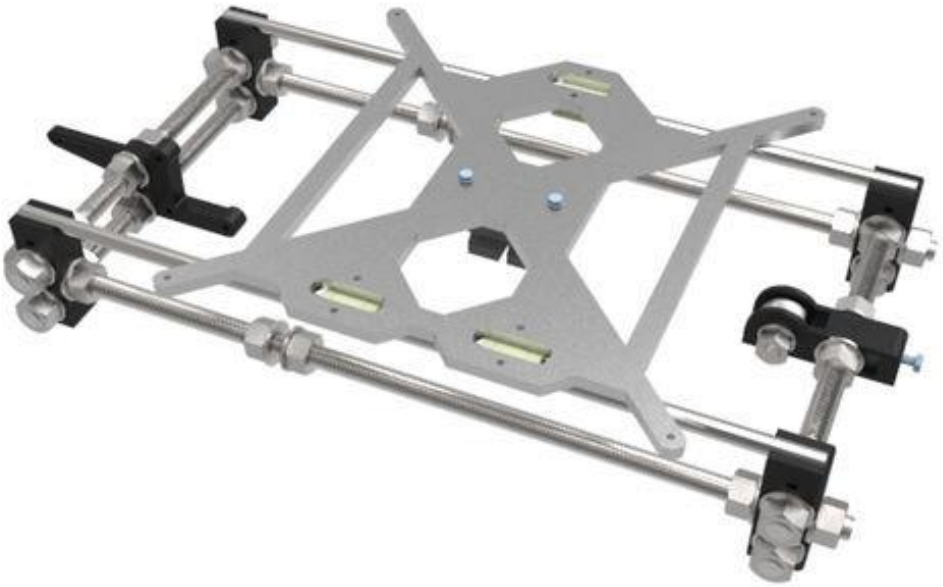
Mechanical structure

	Single Sheet Frame
Plastic Parts (exc Extruder)	26
Non Printed Parts	337 (approx)
Cost	$300 – 1000
Controller Electronics	Almost all RepRap controller
Printing Size	200 x 200 x 200
Motors	5 x NEMA 17 Stepper
Frame Material	6 mm Aluminium (or Wood)
Frame Manufacture	Laser Cutter, CNC, Water Jet
Pro	Easy assembling
Con	Specialised tools

Hardware

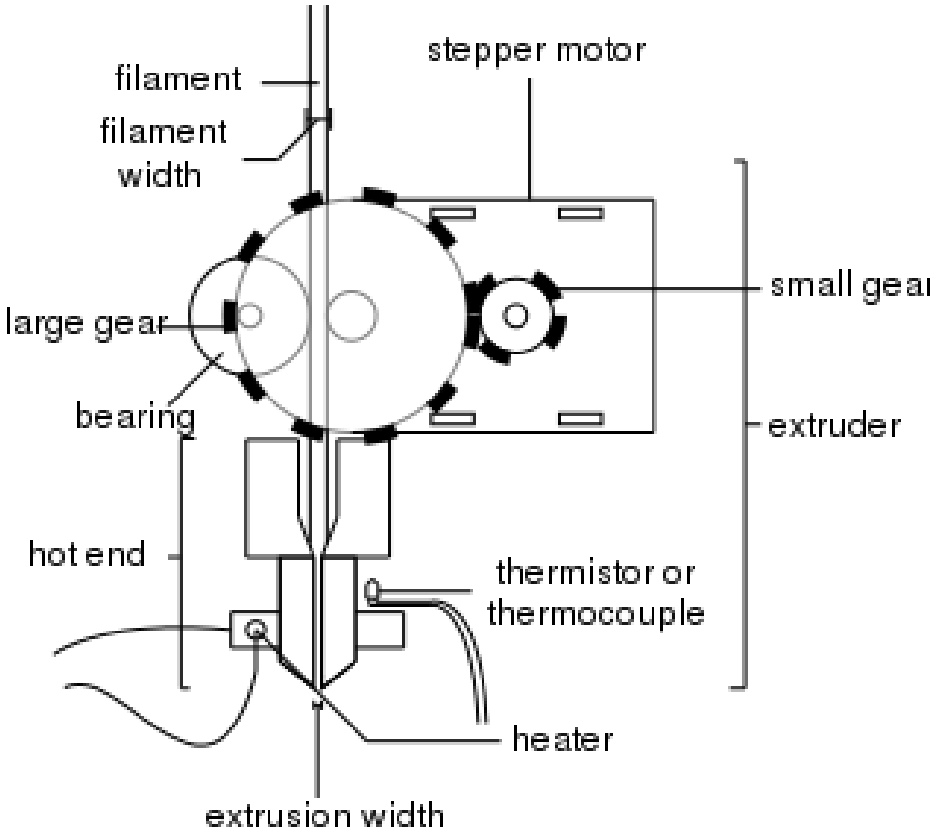
Mechanical structure

- 3D positioner
- Plastic parts + “vitamins”



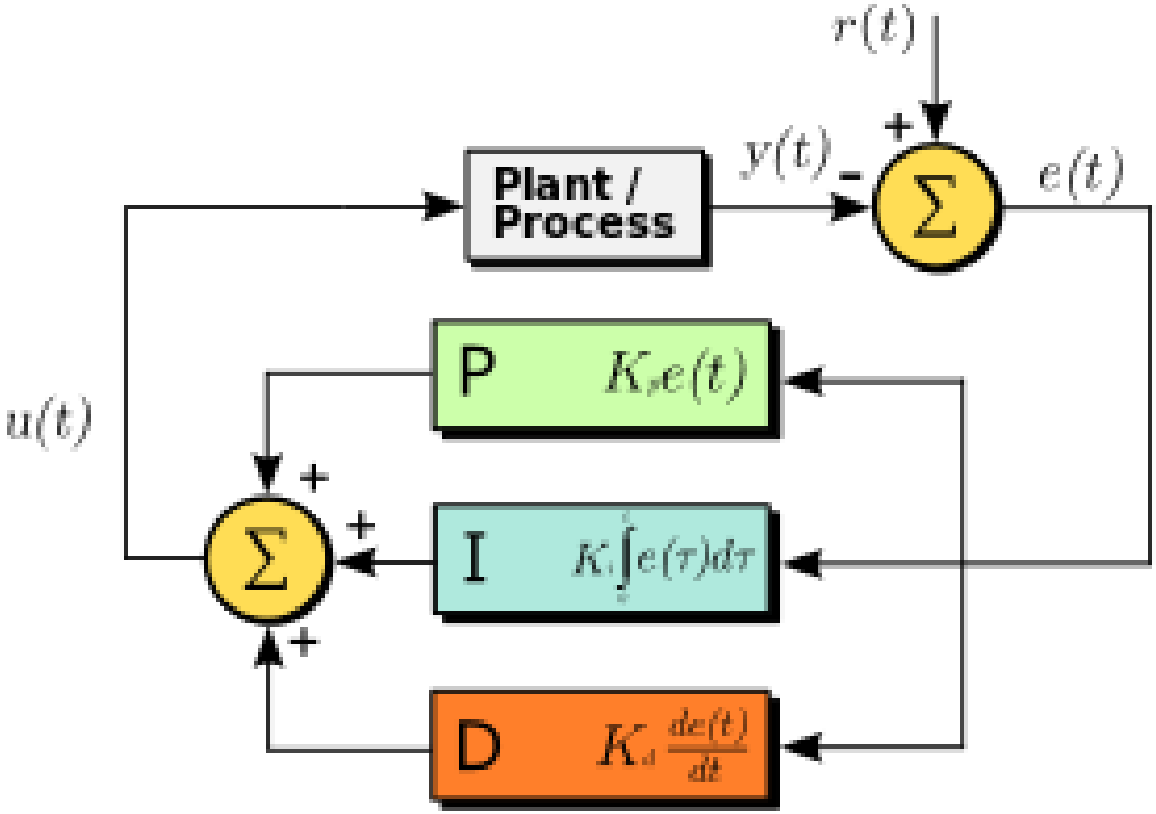
Hardware

Extruder



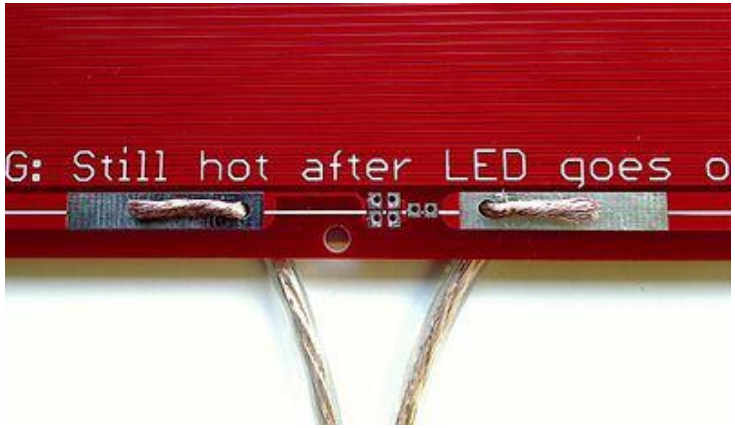
Hardware

Temperature controller



Hardware

HotPlate



Hardware

Electronics

1) Community based, tested and supported electronics
   - 4pi
   - Generation 7 Electronics
   - Melzi
   - RAMPS (RepRap Arduino Mega Pololu Shield)
   - Sanguinololu
   - SmoothieBoard
2) RAMPS derivatives
   - Megatronics
   - 3Drag controller
3) Commercial alternatives
   - R2C2 Electronics
   - Generation 6
   - Generation 4

Firmware (Electronic)

Ramps

RepRap Arduino Mega Pololu Shield

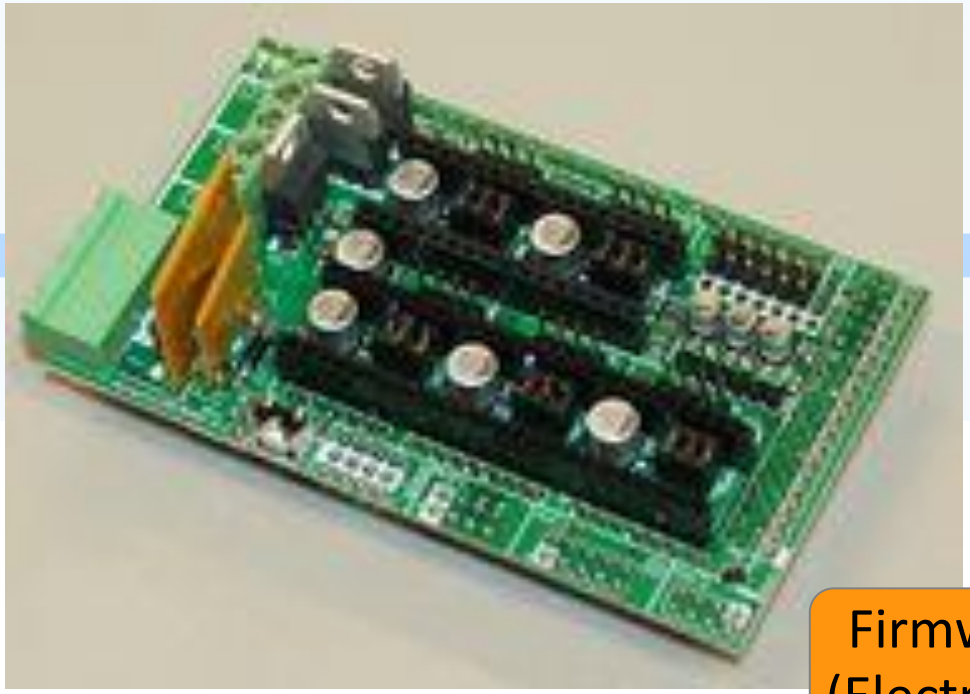
ELECTRONICS INFO	
Details	**Description**
Name : RAMPS **Creator** : johnnyr **Status** : active	Arduino MEGA based modular RepRap electronics. RAMPS is the most often used RepRap electronics in 2012. It shares circuitry concepts (stepper driver, thermistor, heater MOSFETs, etc.) with many other electronics.

Features

- License=GPL
- Built on stable Arduino Mega base
- Modular - easier to troubleshoot
- ATmega based
- up to 1/16 microstepping
- etch resist prepared up to v1.3, v1.4 is optimized for smd

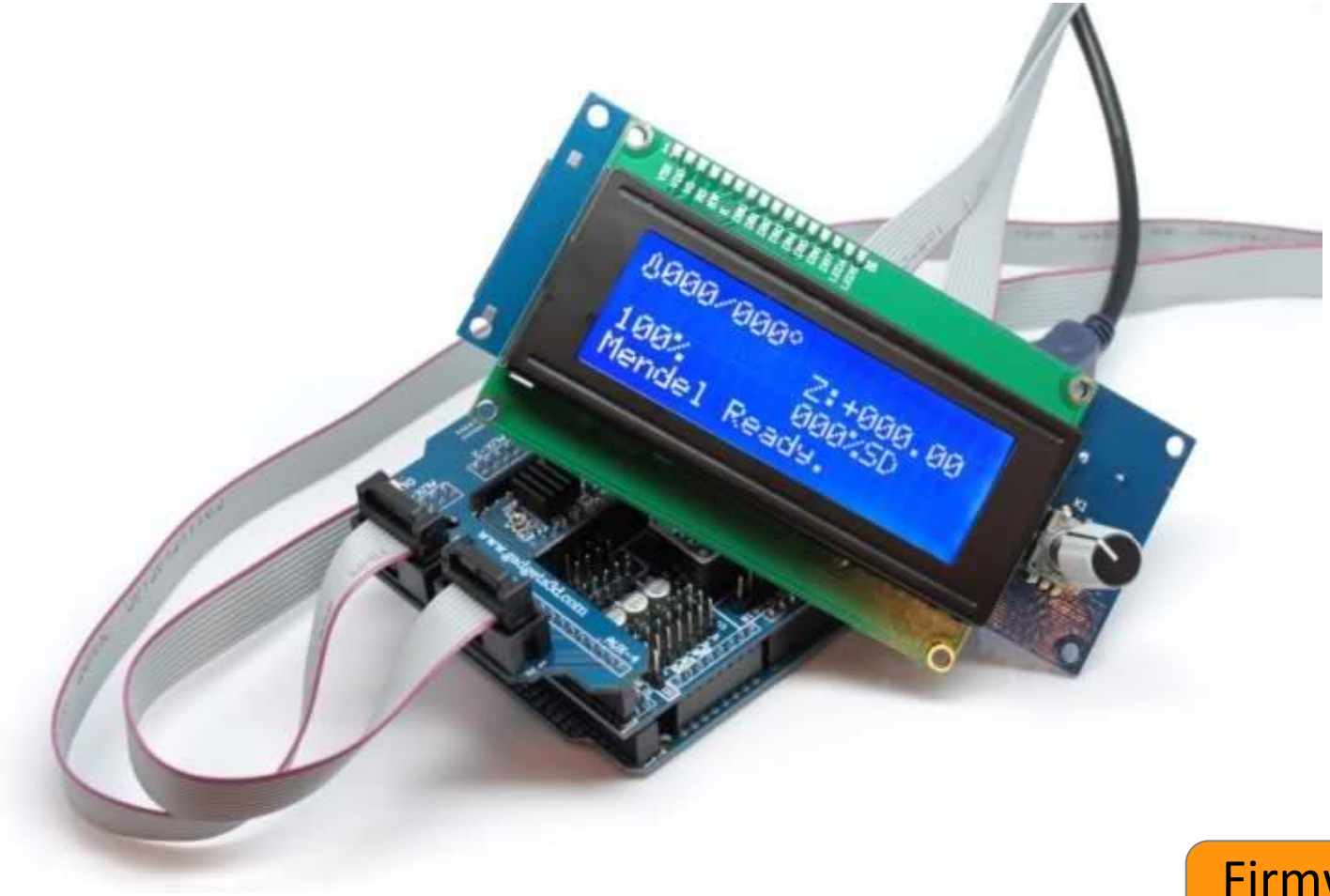
Compatible Firmware

- Marlin
- Sprinter
- Teacup



Firmware (Electronic)

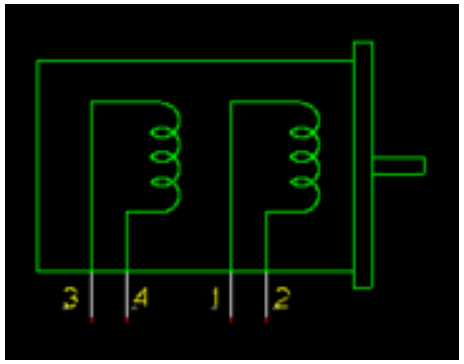
RAMPS GADGETS3D Shield with Panel



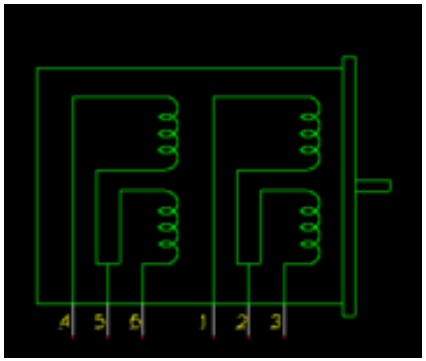
Firmware (Electronic)

Stepper Motors

Stepper motor
(NEMA standard)



Bipolar

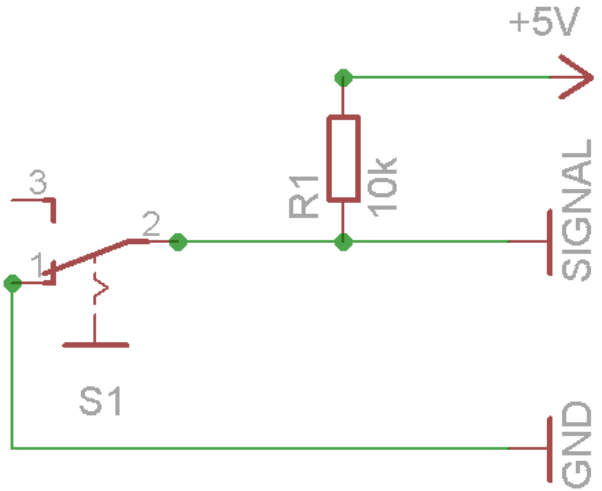


Unipolar

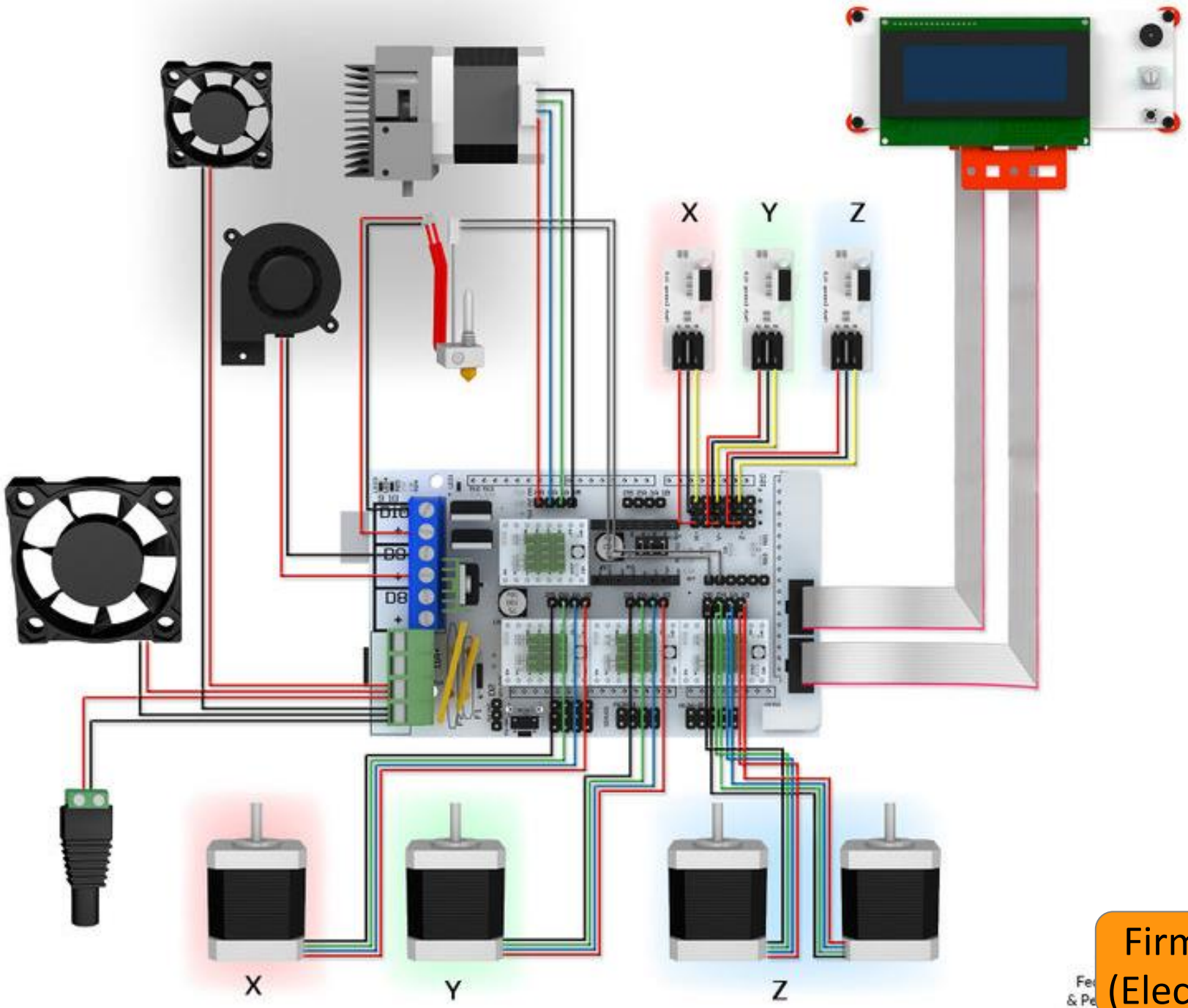
Pololu stepper driver

Firmware
(Electronic)

Mechanical Endstops



Firmware (Electronic)



Firmware (Electronic)

Arduino

ARDUINO

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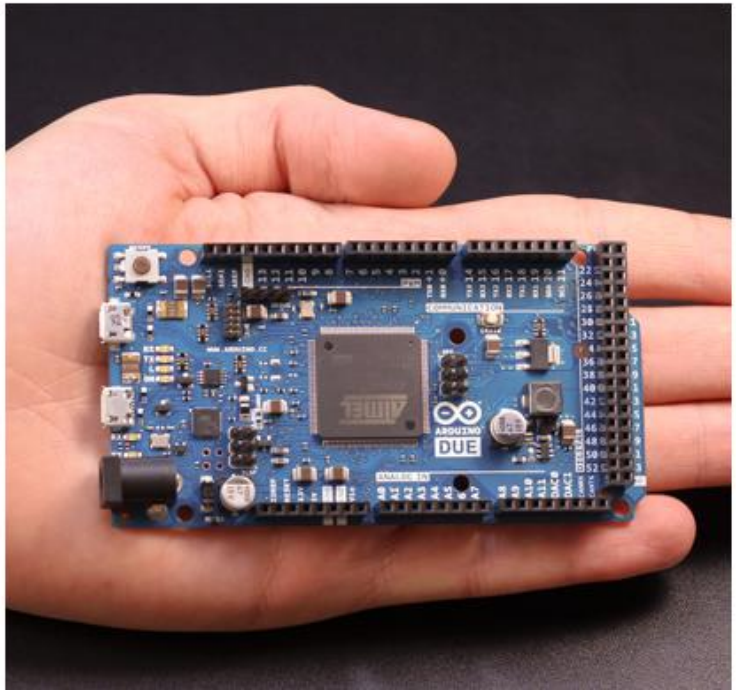
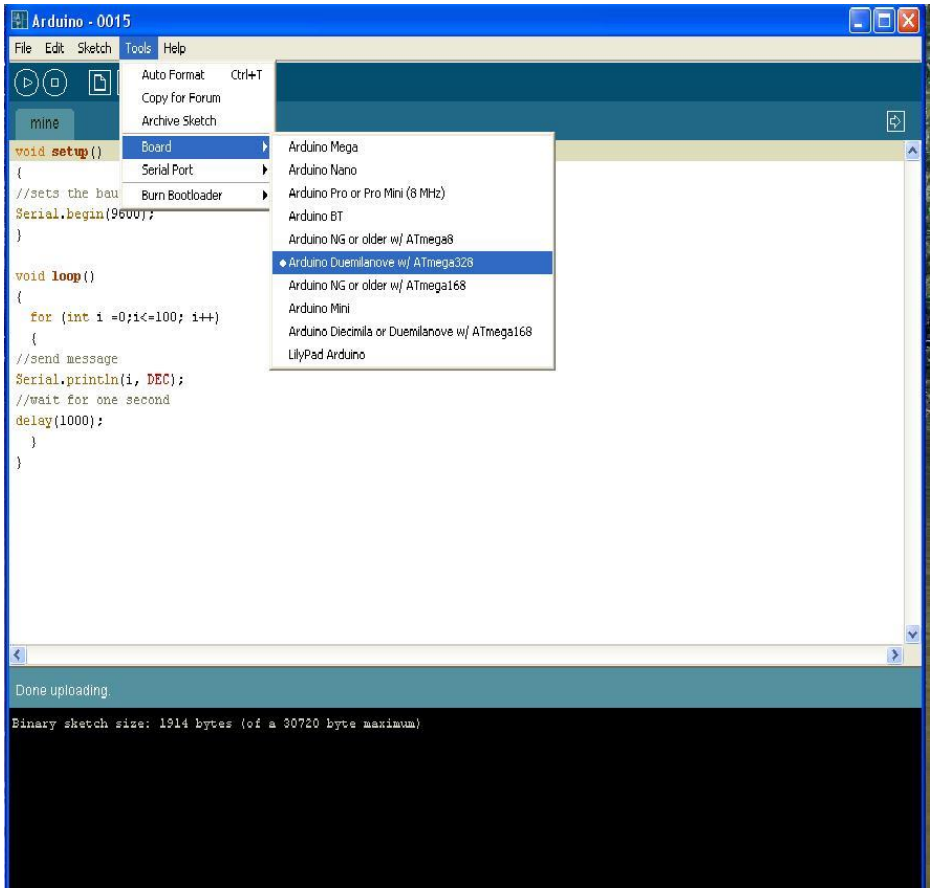


Arduino is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. It's intended for artists, designers, hobbyists and anyone interested in creating interactive objects or environments.

Arduino can sense the environment by receiving input from a variety of sensors and can affect its surroundings by controlling lights, motors, and other actuators. The microcontroller on the board is programmed using the Arduino programming language (based on Wiring) and the Arduino development environment (based on Processing). Arduino projects can be stand-alone or they can communicate with software running on a computer (e.g. Flash, Processing, MaxMSP).

Firmware (Electronic)

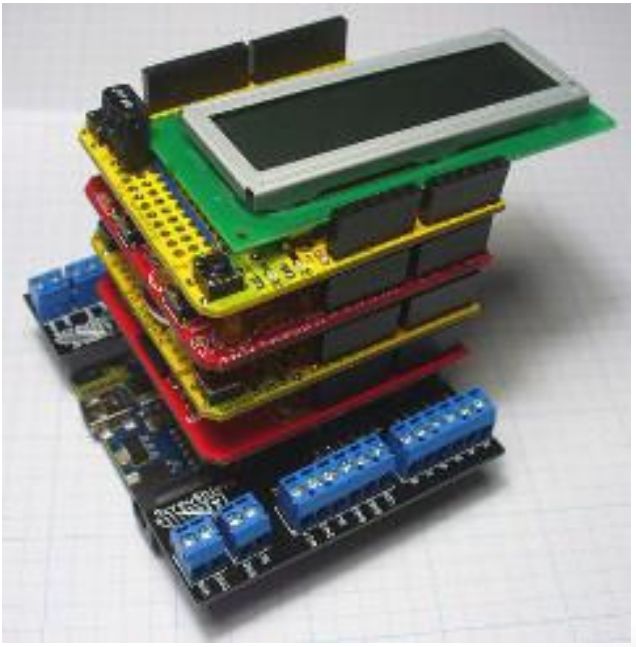
Arduino



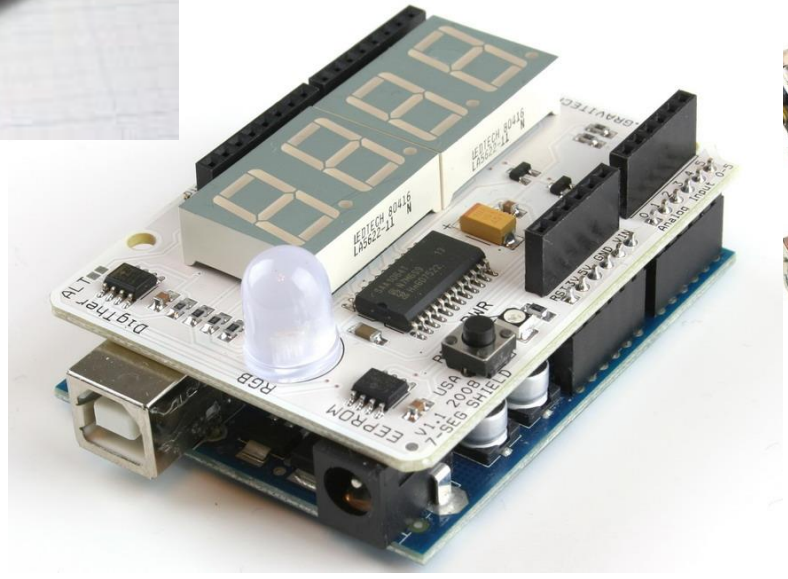
- IDE (Integrated Development Environment)
- The Arduino development environment contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions, and a series of menus. It connects to the Arduino hardware to upload programs and communicate with them.
- Software written using Arduino are called sketches.

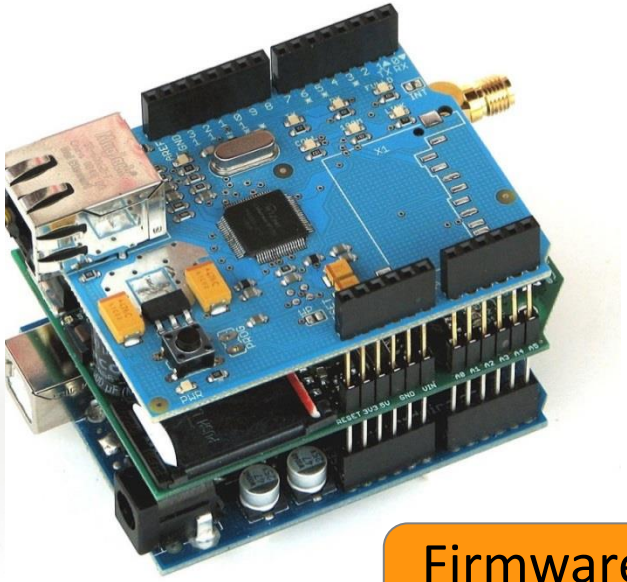
Firmware (Electronic)

Arduino



Shields are boards that can be plugged on top of the Arduino PCB extending its capabilities. The different shields follow the same philosophy as the original toolkit: they are easy to mount, and cheap to produce.

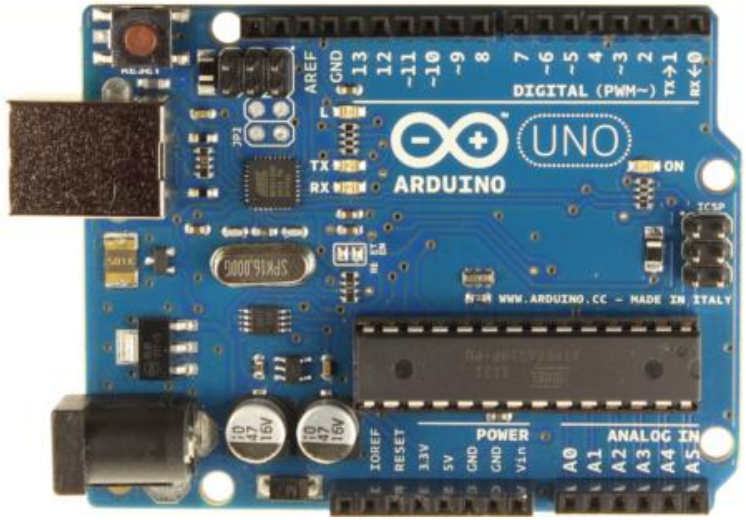




Firmware (Electronic)

Arduino UNO

- The Arduino Uno is a microcontroller board based on the ATmega328.
  - 14 digital input/output pins
  - 6 PWM outputs (8 bit resolution)
  - 6 analog inputs (10 bit resolution)
  - 32 KB Flash Memory (of which 0.5 KB used by bootloader)
  - 2 KB SRAM
  - 1 KB EEPROM
  - 16 MHz ceramic resonator
  - USB connection - ICSP header
  - Power jack - reset button

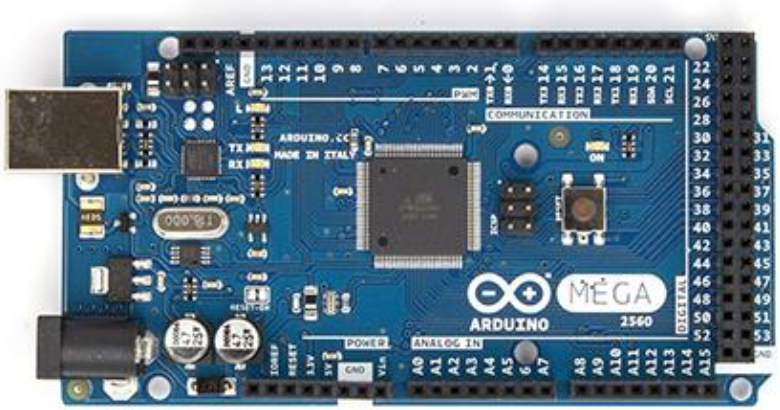


- It contains everything needed to support the microcontroller
- simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

Firmware (Electronic)

Arduino Mega

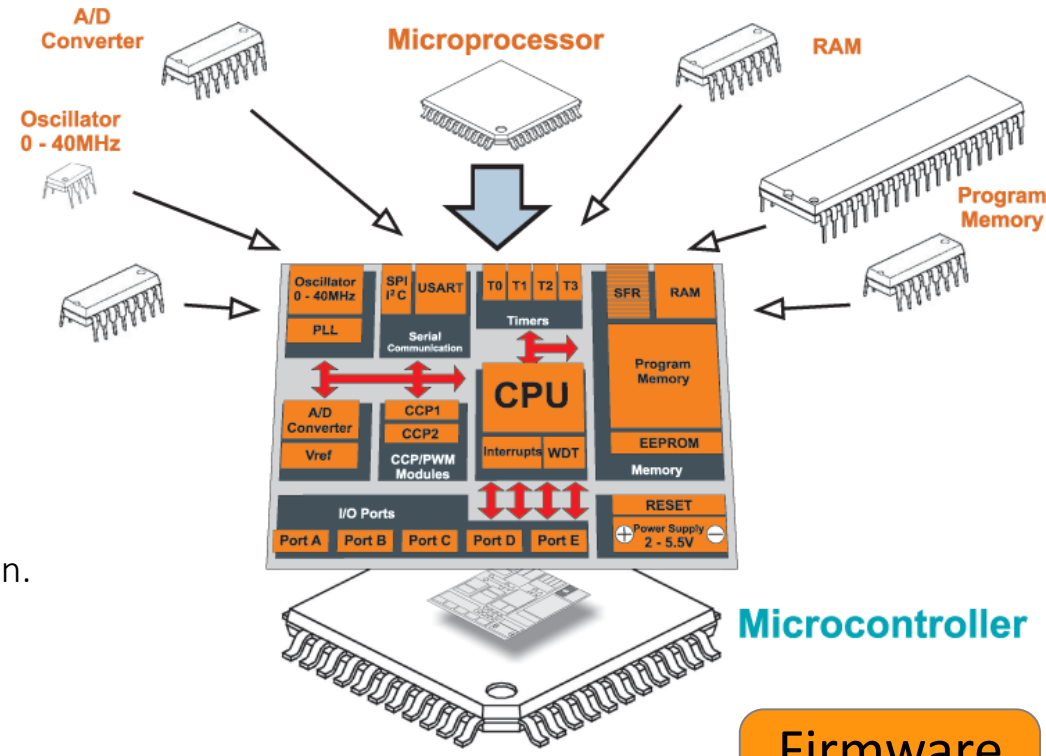
- The Arduino MEGA is a microcontroller board based on the ATmega2560.
  - 54digital input/output pins
  - 15 PWM outputs (8 bit resolution)
  - 16 analog inputs (10 bit resolution)
  - 256 KB Flash Memory (of which 8 KB used by bootloader)
  - 8 KB SRAM
  - 4 KB EEPROM
  - 16 MHz ceramic resonator
  - USB connection - ICSP header
  - Power jack - reset button



Firmware (Electronic)

Difference between microprocessor and microcontroller

- Microprocessor is an IC which has only the CPU inside them. It doesn't have RAM, ROM, and other peripheral on the chip. Application of microprocessor includes Desktop PC's, Laptops, notepads etc.
- Microcontroller has a CPU, in addition with a fixed amount of RAM, ROM and other peripherals all embedded on a single chip.
- Microcontrollers perform specific tasks where the relationship of input and output is defined.
- Microprocessor find applications where tasks are unspecific like software, games, websites, photo editing
- Microcontroller doesn't have video output.
- Microcontroller are programmed with firmware
- Microprocessors run operating systems on which software applications run.



Firmware (Electronic)

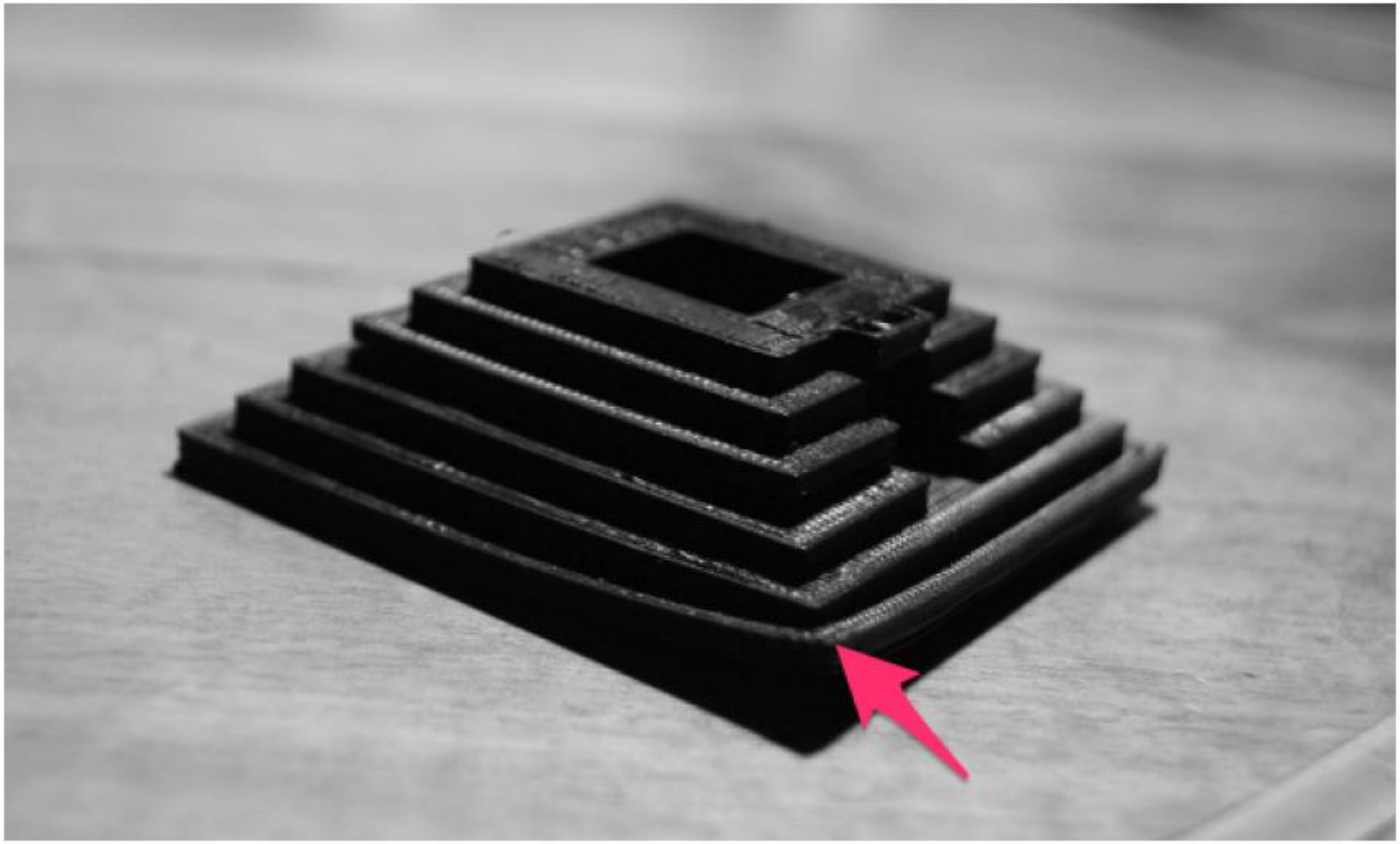
Firmwares

- List of firmwares
  1. Sprinter
  2. Teacup
  3. sjfw
  4. Marlin
  5. Sailfish
  6. Makerbot
  7. Grbl
  8. Repetier-Firmware

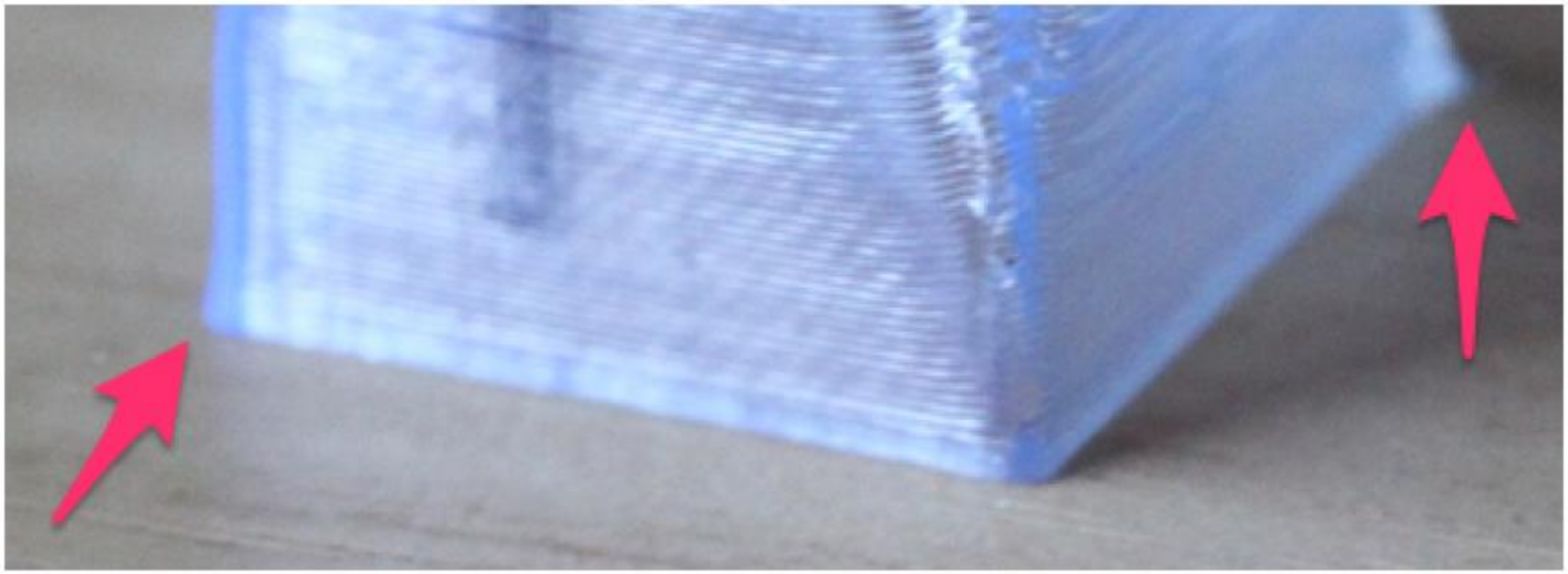
Firmware (Electronic)

COMMON PROBLEMS WITH (LOW COST) FDM SYSTEMS

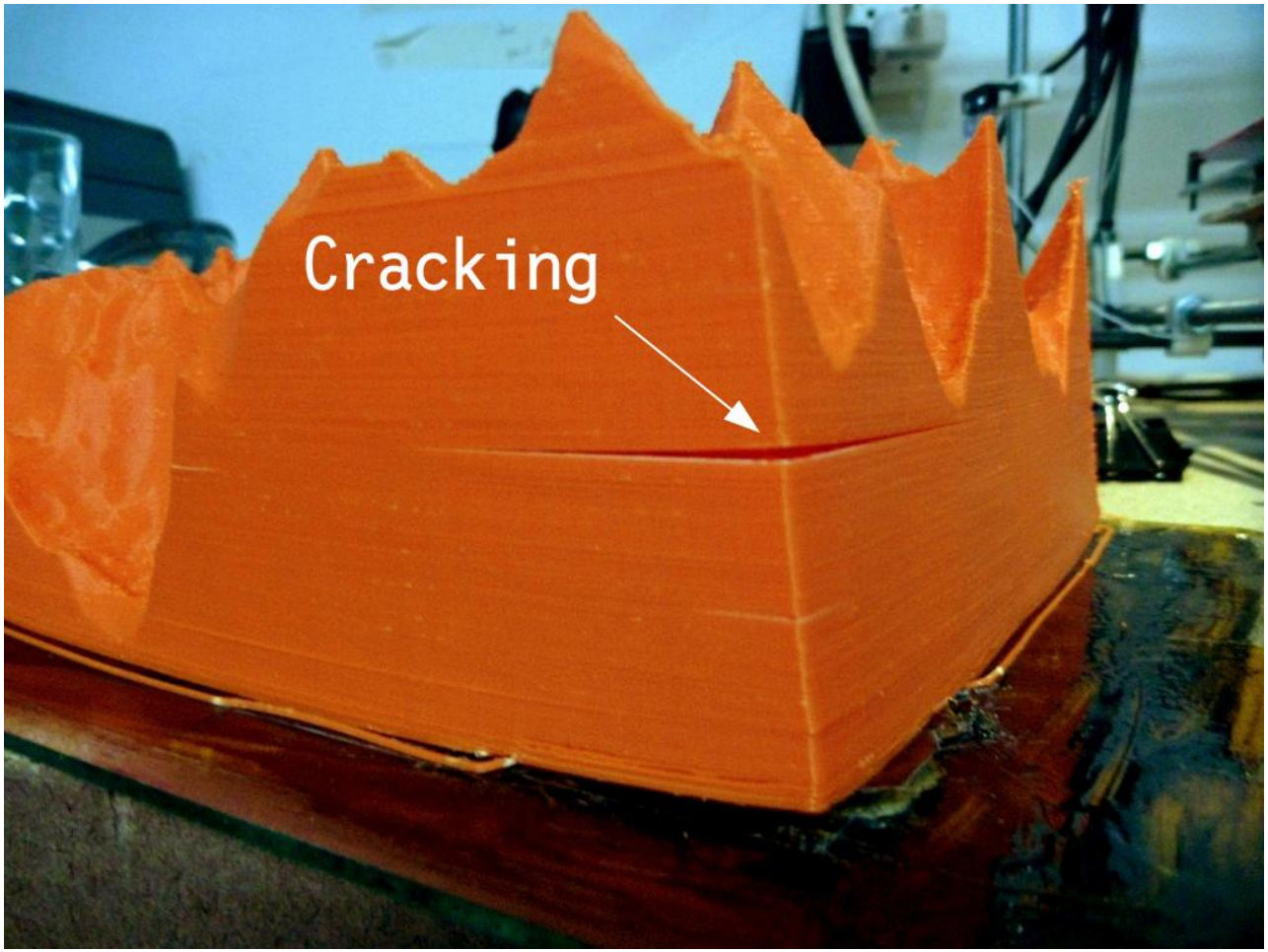
Warping



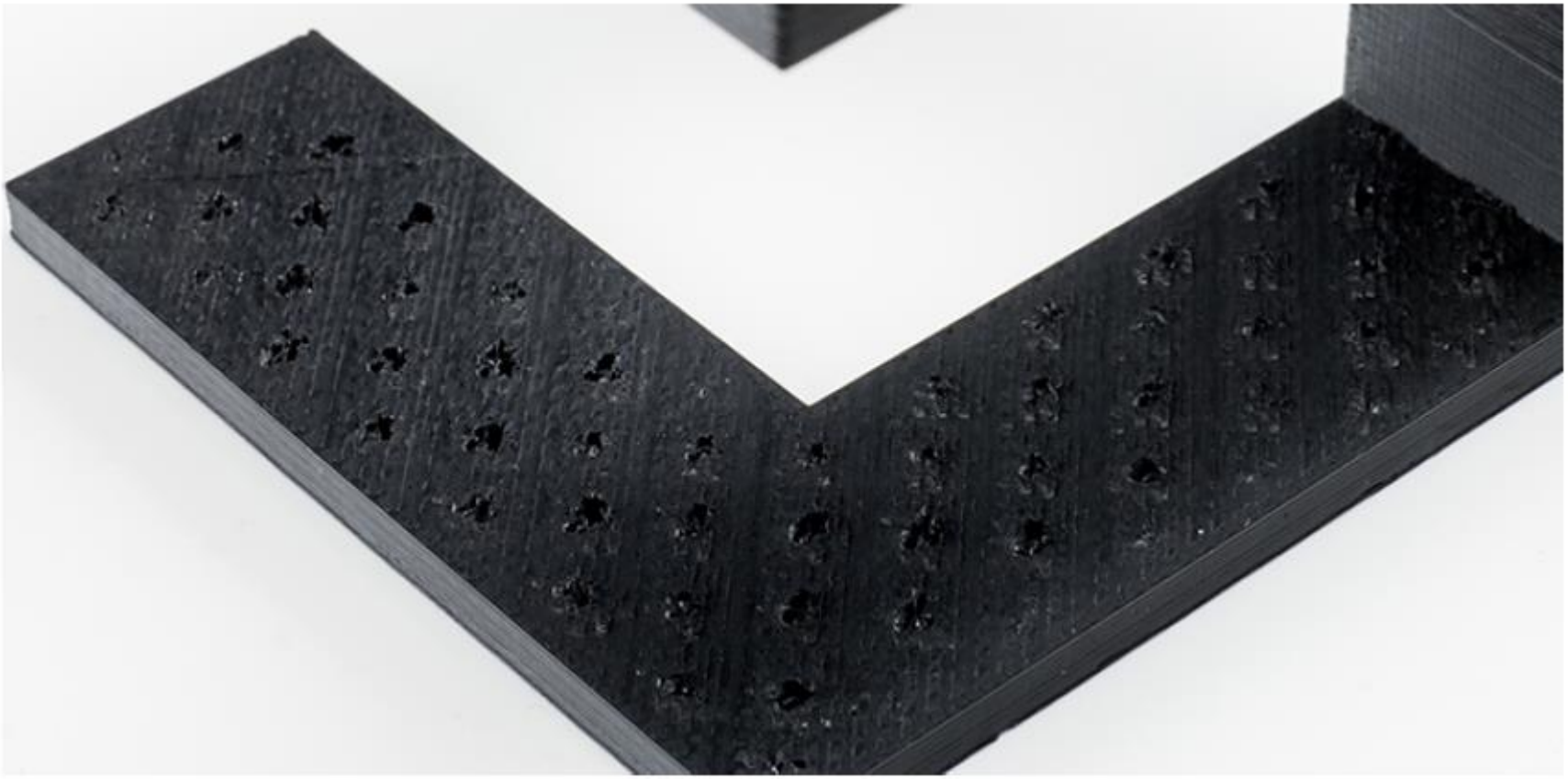
Elephant foot



Cracks in tall objects



Pillowing



Stringing