Summer Student Programme 2016 – Student Report

3D Printing the ATLAS' Barrel Toroid

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1 Introduction

The present report summarizes my work as part of the Summer Student Programme 2016 in the CERN IR-ECO-TSP department (International Relations – Education, Communication & Outreach – Teacher and Student Programmes). Particularly, I worked closely with the S'Cool LAB team on a science education project. This project included the 3D designing, 3D printing, and assembling of a model of the ATLAS' barrel toroid.

1.1 S'Cool LAB

S'Cool LAB (http://cern.ch/s-cool-lab) is an international out-of-school hands-on learning laboratory for high-school students at CERN. The students (ages 16-19) work with high-tech equipment to perform experiments related to particle physics. These experiments are designed to guide the students to a better understanding of the research done at CERN and of particle physics in general.

1.2 ATLAS' Magnetic System

The ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) magnet system is made up of superconducting electromagnets arranged in a central solenoid, a barrel toroid and two end-cap toroid, as shown in Figure 1. Each toroid is made up of eight coils. Figure 2 shows the barrel toroid at the time when the ATLAS detector was being assembled. The person in the figure gives an idea of the size of the detector. The barrel toroid is 25.3 m in length and has an outer diameter of 20.1 m [1]. The toroid magnets generate a magnetic field where the muon chambers are accommodated, allowing the study of the muons' properties such as their momentum.

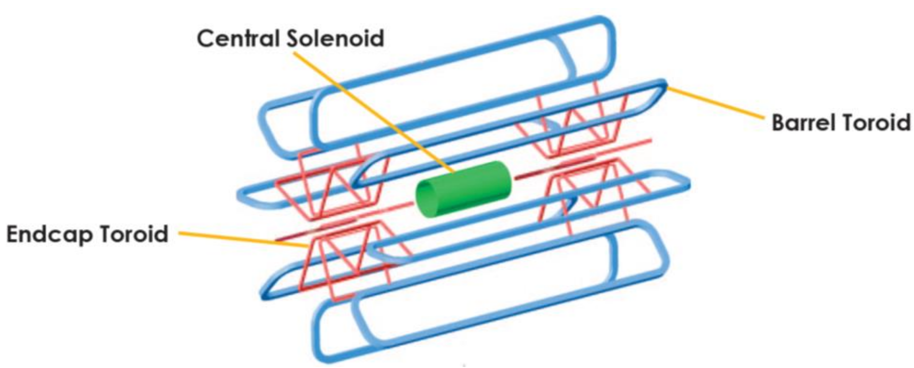


Figure 1. Magnet system of the ATLAS detector [1].

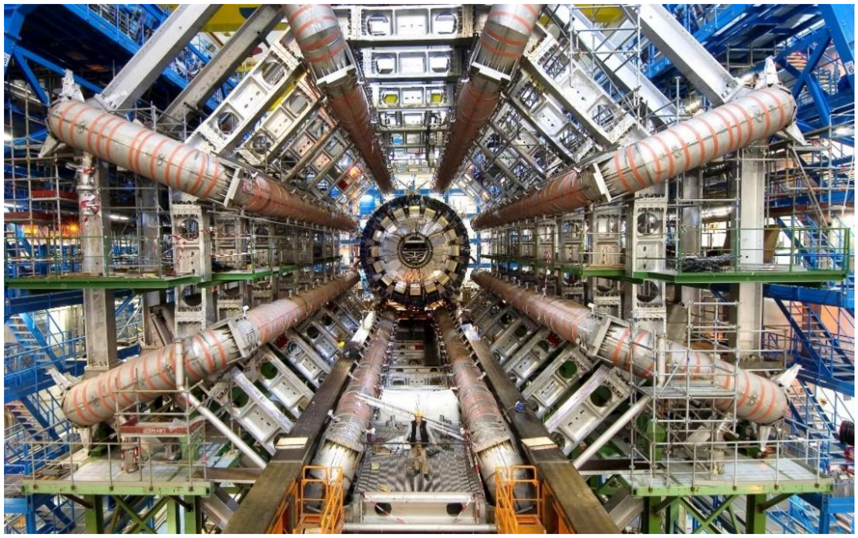


Figure 2. The barrel toroid during the assembly of the ATLAS detector (CERN, 2005).

1.3 PROJECT

The first prototype of a model of the ATLAS' barrel toroid was built in the context of the International Teacher Programme 2014. The model consists of eight coils of normal conducting copper wire. Such a model is intended for students to explore how the magnetic fields from each coil add up together and visualize the shape of the magnetic field in ATLAS. Students can also predict how particles emerging from the collision point would be deflected in the magnetic field.

Since then, models have been done either using cardboard and straws as a support structure for the coils, or using acrylic glass.

As 3D printers become more affordable and widely available, they are becoming a powerful teaching resource at schools. In this context, we were interested in producing a more professional looking model using 3D printing. The idea is to make all 3D files available for anyone to print and build its own model. The process of designing, printing, and assembling made up the bulk of my project done with the team, and is described in more detail below.

2 PROJECT DEVELOPMENT

2.1 LITERATURE

Before the designing phase, it was necessary to do research and understand the characteristics of the ATLAS magnetic system, particularly the barrel toroid [1, 2]. Ideas of how to draw the different pieces so that they can be easily and successfully assembled together, as well as resemble the real detector, were drawn from A. Foussat *et al.* (2006) [3].

2.2 DESIGNING

Searching through the varied 3D designing software available, *FreeCAD 0.16* was chosen. The reasons being that FreeCAD is an open-source software, is not overcomplicated for beginners but still shows to me great potential for advanced use.

A model scaled 1:100 to the real detector was desired. Given its dimensions (approximately 25 cm length and 20 cm of outer diameter), it would be impractical to print the model in a single piece. Therefore several components were designed separately, in a way that would allow the assembly. In the end, making use of the barrel toroid's symmetry, the whole model was designed based on only four different pieces.

The key component is the *coil frame* – the structure where the copper wire can easily be winded to make the coils (see Figure 3 (a)). Because of the required size, the coil frame was designed in two identical halves with a jigsaw-puzzle-like connection between them.

To connect the 8 coils, two different pieces were designed – an *inner strut* and an *outer strut* (see Figure 3 (b) and (c)). Eight inner struts are necessary to make one complete inner ring while eight outer struts make up an outer one. These struts were designed with hollow surfaces and holes in order to both resemble the real detector as well as to use less printing material while keeping the structural support.

Based on the real detector, a *foot* design was also developed (see Figure 3 (d)). In this way, the model can be sustained from the ground with feet holding the two bottom coils.

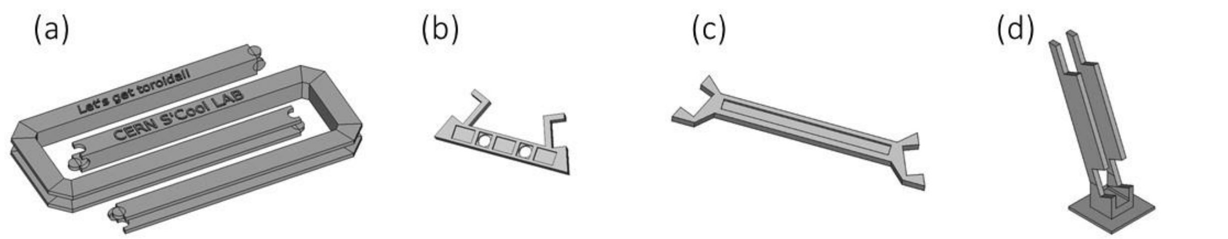


Figure 3. 3D designs of each component (not to scale). (a) Coil frame (two halves), (b) Inner strut, (c) outer strut and (d) foot.

2.3 PRINTING

In this way, to make a complete model, one needs to print 8 coil frames, and at least 16 inner struts, 16 outer struts and 4 feet. These amount of struts is the necessary to make two inner and two outer rings. Note that in the real detector the barrel toroid is made up of a total sixteen rings of struts. However, four rings are enough to support the lightweight model and in this way there is more free space to probe the magnetic field.

Before printing using Fused Deposition Modeling (FDM) technology, it is necessary to use a 3D printing slicing software, which divides the 3D model in layers and actions for the printer. The chosen software was *Cura 15.04.6* which is associated with the 3D printer used - *Ultimaker 2+*.

The pieces were printed with PLA plastic. Some pieces are best printed with brims and support structures which must be removed afterwards. Figure 4 shows a part being printed.

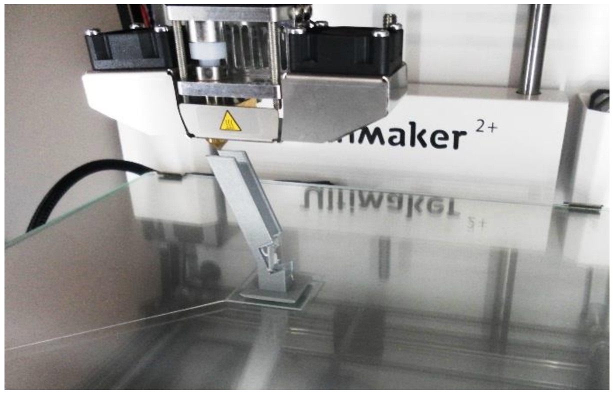


Figure 4. Printing a foot.

2.4 Assembling

After printing all the necessary pieces, and remove any excess of plastic, the first step was to build the coils. Started by gluing the two halves of each coil frame, in order to avoid the deformation of the coils under the wire tension. Each coil has 80 turns of enamelled copper wire. In the coil frame two small holes were drilled. One for the starting point of the wire, the other for the end point.

With the coils completed, the whole model is glued together for more stability. The glue should be appropriate for PLA. A multipurpose cyanoacrylate (common super glue) was used. The wires are soldered together to connect the coils in series. That way that the magnetic fields from each coil add up around, making the toroid. The two bottom coils are left unconnected; instead each is associated with a connector where leads can link the model to a power supply. The holes in the inner strut ring became very useful support for the connectors.

It is interesting to remark that when the real detector was assembled, care needed to be taken so that the toroid, with a total mass of 870 t, had a final cylindrical shape, with a tolerance of +/- 10 mm with respect to an overall system diameter of the order of 20 m. For this purpose, the toroid had to be installed in an elliptical shaped structure before releasing it under its own weight [3]. No such care was taken when designing and assembling the model.

Figure 5 shows some pictures of the completed model that can be compared with Figure 2.

Figure 5. Pictures of completed model. Bottom right: connected to a power supply and ammeter measuring 0.39A.

3 Results

Table 1 compares characteristics of the model to the real ATLAS barrel toroid.

Characteristics	ATLAS Barrel Toroid	3D Printed Model
Inner diameter (m)	9.4	9.3×10^{-2}
Outer diameter (m)	20.1	20.1×10^{-2}
Length (m)	25.3	24.7×10^{-2}
Mass (kg)	8.3×10^{5}	0.86
Conductor material	Al/NbTi/Cu	Enamelled copper wire
Turns per coil	120	80
Conductor length (m)	5.6×10^{4}	5×10^{2}
Operating temperature (K)	4.5	Room temperature
Voltage (V)	16	12
Resistance (Ω)	1.6×10^{-4}	31
Current intensity (A)	2.05×10^{4}	3.9×10^{-1}
Field strength (T)	3.9	8×10^{-4}

Table 1. Comparison between real barrel toroid [1, 2] and model.

In a classroom setting, the model can be used to discover the magnetic field shape with a compass, or a 3D compass (one was also printed, see Figure 6). The 3D file is available at thingiverse.com/thing:1722286. Also to measure the field strength using a smartphone or Hall probe. Or even to explore how charged particles would move in the real detector, using, for example, an electron tube (see Figure 7).

Figure 6. 3D magnetic compass printed as part of the project.

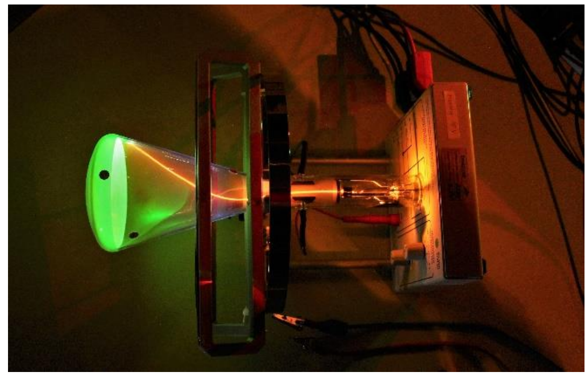


Figure 7. Electron beam deflected by two coils of the model.

4 Conclusion

The end result of my project was a beautiful and working model of the ATLAS' barrel toroid. Additionally, I produced videos explaining why and how to build the model, and how it can be used. These will accompany the 3D model when it becomes available from thingiverse.com/thing:1722230. This will probably happen when a paper related to the model and its educational potential is published in a physics education journal. Furthermore, during the course of this project I've also wrote a small manual of how to use the software to design and 3D print to facilitate future projects. This manual is available here in the appendix.

5 References

[1] ATLAS Outreach. ***ATLAS Fact Sheet: To raise awareness of the ATLAS detector and collaboration on the LHC***. ATLAS Brochure (2010). (https://cds.cern.ch/record/1457044)

[2] ATLAS Collaboration. ***The ATLAS Experiment at the CERN Large Hadron Collider***. J. Instrum. 3 (2008). (http://cds.cern.ch/record/1129811)

[3] Foussat, A. *et al.* ***Assembly Concept and Technology of the ATLAS Barrel Toroid***. IEEE Trans. Appl. Supercond. 16 (2006). (http://cds.cern.ch/record/1071134)

6 APPENDIX

From Ideas to 3D Prints

Hardware : Ultimaker2+ ¦ **Software** : FreeCAD 0.16; Cura 15.04.6

I. Designing in FreeCAD*

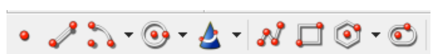
(*For good introductory video tutorials: https://www.youtube.com/watch?v=xs1mFiJBYIo for Part 1 and then following Parts.)

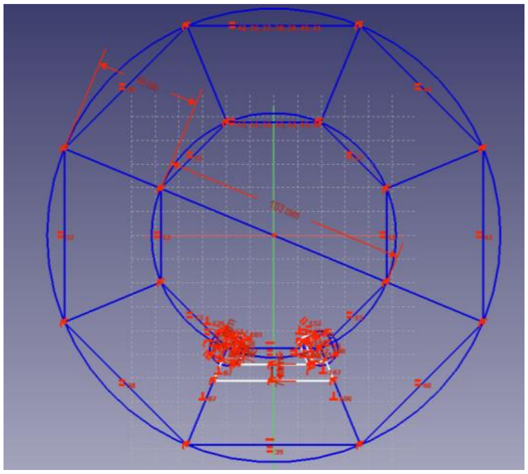
- ✓ Two main different ways of making 3D objects– from basic shapes or from 2D sketches.
- ✓ Can join or subtract solids from each other.
- ✓ (The software also allows for codding with python).

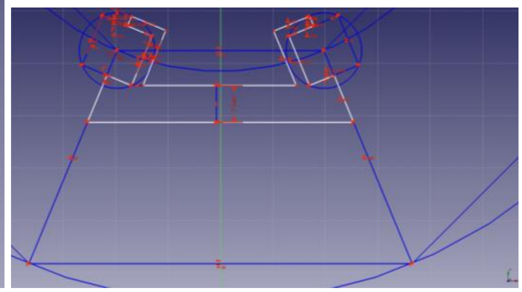
A. Starting from basic shapes

1. Workbench: “Part”.
2. Choose solids. 

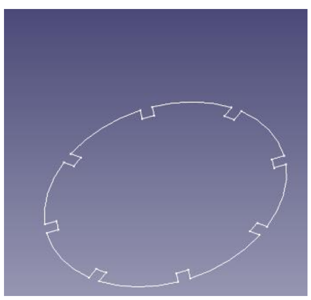
B. Starting from 2D Sketch with Constraints

1. Workbench: “Sketcher”.
2. Click on  symbol (“Create a new Sketch”).
3. Choose Sketch plane.
4. Draw sketch using the different tools .
5. Can create constraints using . This allows to define lengths, radii, etc., but also geometric relations between elements such as symmetries.
6. Can make auxiliary lines, that will not be part of the sketch but that help to make constraints for example. To do this use the button . Auxiliary lines will appear in blue.

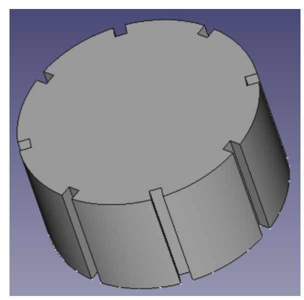


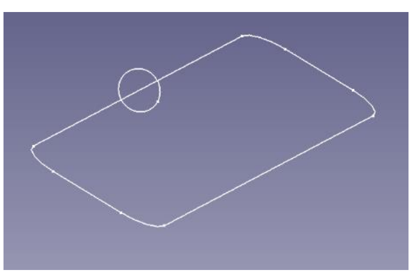


7. to do 3D object from the 2D sketch:
    a. In the "Part Design" workbench, can use "Pad" .
    b. Or in "Part" workbench can use "Utility to sweep" by defining a contour and a path to sweep that contour. Tick the option "create solid" if desired.
    c. Or in "Part" workbench, can use "Utility to loft" , to create a solid between two different sketches.
    d. Examples:

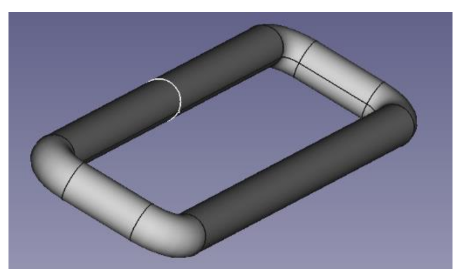


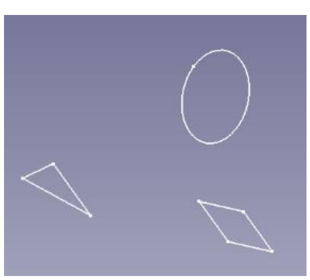
Pad



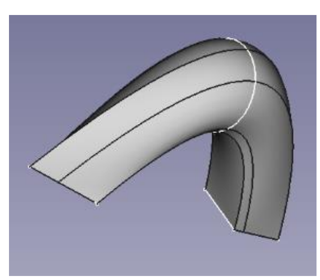


Sweep



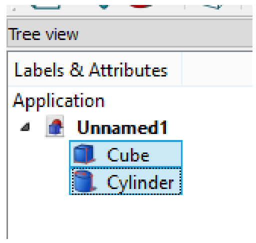


Loft

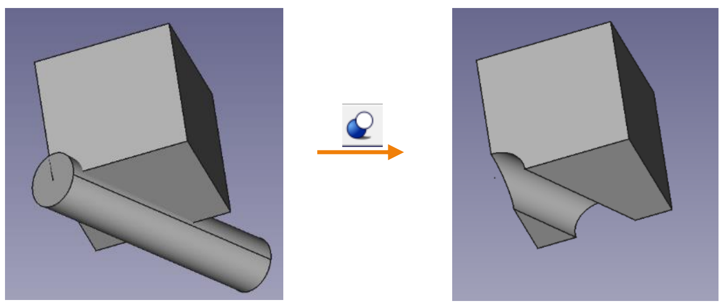


C. Adding or subtracting solids

- ✓ In the "Part" workbench there are several options to combine different shapes .
- ✓ Need to select the shapes on the "Tree view" on the left hand side:



- ✓ Example of "Make a cut of two shapes"  :



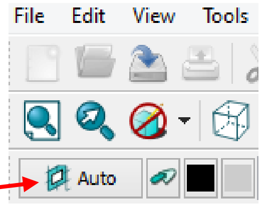
C. Producing Pictures of the Model

- ✓ Possible by going to "Tools" > "Save picture…"
- ✓ Can choose advanced options by clicking in "Extended".
  - o Example can choose white background under "Image properties" and set "Background:" to "White".
- ✓ If it fails to save the picture, i.e. if it doesn't produce any figure file [I only needed to do until step 6]:
  1. Go to "Tools" > "Edit parameters"
  2. Then go to "Preferences" > "Document"
  3. Right click to create a "New Boolean item"
  4. Enter the name "DisablePBuffers" and set it to "true"
  5. Restart FreeCAD
  6. If it still doesn't work change it to "false". Restart FreeCAD.
  7. If it still does't work create Boolean key CoinOffscreenRenderer and set it to "true". Restart FreeCAD.
  8. If it still then close FreeCAD and set the environment variables:

     Code:

```
COIN_GLXGLUE_NO_PBUFFERS=1
COIN_GLXGLUE_NO_GLX13_PBUFFERS=1
```

D. Making 3D letters

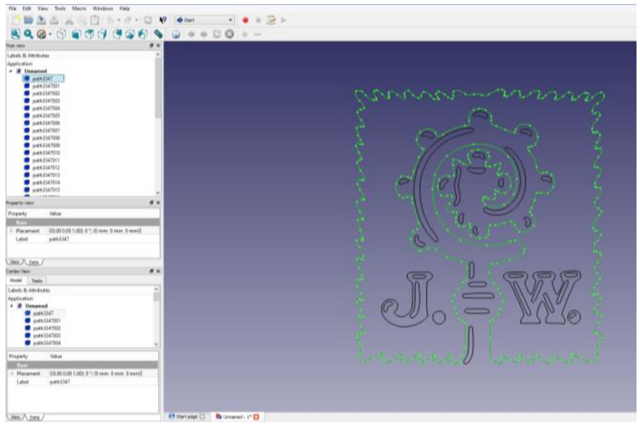
1. Open “Draft” Workbench
2. Click in this button 

 and then click on the surface you want to be the plane to draw the letters.
3. Click on the  symbol.
4. Click on the surface on the point you want the text to start from.
5. Write the desired text on the “String” box and press Enter.
6. Choose height (height of the text font) and press Enter.
7. Press Enter (Tracking = 0mm).
8. To choose path to font file click on the “…” and search for “fonts” folder and then choose a file (e.g. inside “ttf” folder).
9. Go to “Part design” workbench, in the “Tree view” select the ShapeString you’ve just created. And then just click on “Pad” , choosing the depth of the 3D letters.

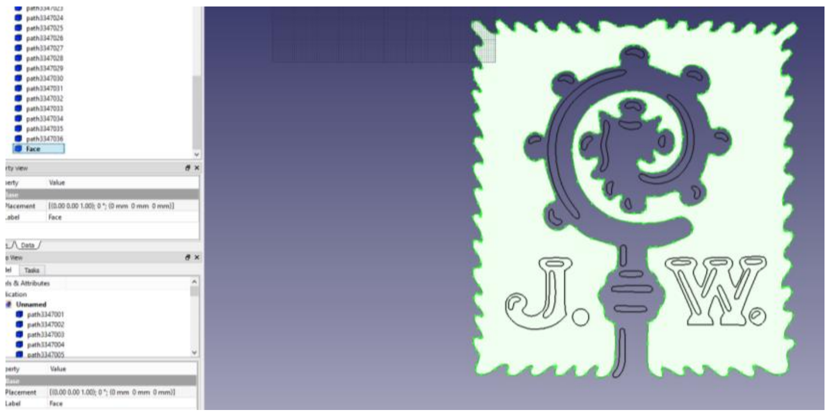
E. Making a 3D File from a flat image

1. Choose the image you want to transform into 3D. The higher resolution and contrast the better. For example:

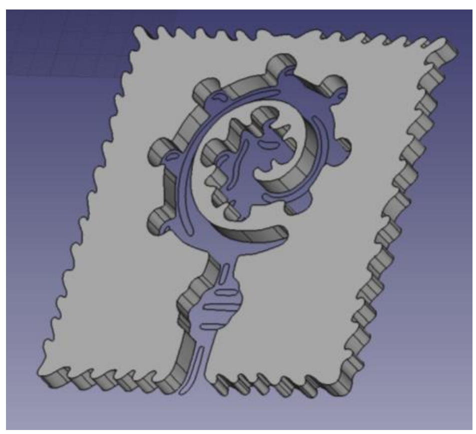
2. Open it with Inkscape (free software).
3. Select the image and in the menu click Path > Trace Bitmap… This will create a vector image, i.e. the paths necessary to draw the picture.
4. Save it as .svg file.
5. Open the .svg file in FreeCAD. (Import svg as: SVG as geometry)



6. Select a Path and in the “Draft” workbench click on  to create a surface.



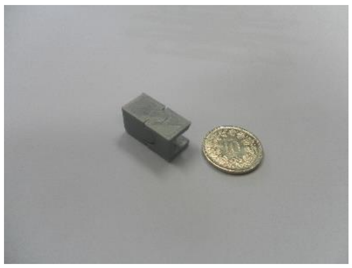
7. Select the Face and in the “Part” workbench click on  to extrude the surface into a solid.



F. Notes

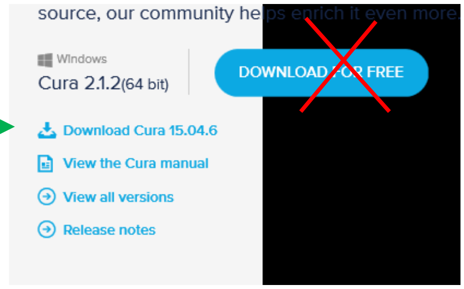
✓ I would say to give the printer a margin of ~0.2mm, that is if want to make two pieces to connect each other make the smaller one about 0.2mm smaller to make sure it fits:

- ✓ I recommend that before printing a large piece to test before. For example test if connections will work by printing the same connections in a small piece, for example:

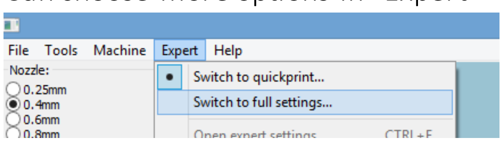


II. Printable file in Cura*

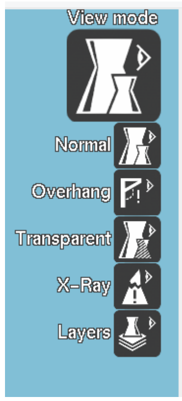
*If the Cura version you downloaded doesn't work you might need to try another version:



- ✓ When you have a 3D model in FreeCAD, to print it you need to use a 3D printing slicing software (e.g. Cura for Ultimaker printers).
- ✓ In FreeCad:
    1. Sellect in the "Tree view" the shapes we want to print.
    2. Export as a .STL file ("File" > "Export…")
- ✓ In Cura:
    1. Load .STL file .
    2. Can choose more options in "Expert" > "Switch to full settings":



        - In "Basic" > "Support" > "Platform adhesion type" better to change from "None" to "Brim". This will print a base on which the object is print that is easily removed afterwards and which helps the first layers to maintain the proper shape. By clicking in the "…" button can choose more options.
        - In "Basic" > "Fill" > "Bottom/Top thickness (mm)" can change to a smaller number to make it faster. This tells how many layers are considered bottom/top, and the speed of print can be adapted differently for bottom, intermedium and top in order to make it faster. However, faster printing usually means less quality.
        - In "Basic" > "Fill" > "Fill density" can choose how much to fill inside the solid parts. This creates a support structure inside the solid without filling all the space. At least for large objects a value of 5% seems to work just fine.
    3. On the right hand side can chose different View modes, for example "Layers" how the printer is going to make each individual layer.



4. Connect the printer's SD Card to the computer. (If you don't have a SD card reader, I've used my photographic camera and works fine).
5. Click on the symbol to save (it will save the printable file automatically on the SD Card. <u>Eject safely before removing SD card.</u>

✓ <u>Tips:</u>

- It might be better to print a piece at a time because if some error occurs in one of them chances are it destroys all of the printing.
- Position the piece in the best way possible thinking how the printer is going to print in layers, and the larger the surface on the bottom the most probable it is for the plastic to curl on the base and come off the building plate destroying the print.

III. Using Ultimaker 2+

Initial

- ✓ Connect the power cable **first** to the wall socket **and then** to the printer, making sure the switch in the back of the printer is in the OFF position.
- ✓ Make sure the power cable is clicked properly into position (need to pull a the black envelope hold it click in the cable and release).
- ✓ **Follow instructions on the display**. Navigate the menu options by rotating the button in the front, and select options by pushing button.

Printing

- ✓ Use Cura software to convert and upload the file for printing into the SD card.
- ✓ If want to use a different nozzle (head tip), need also to select the appropriate one when preparing the file on Cura software.
- ✓ Before printing **clean the build plate surface** (with a wet tissue and dry).
- ✓ Occasionally, level the build plate (Maintenance > Build Plate).

Changing Filament

Removing

- ✓ Go to "Material" > "Change" in the main menu.
- ✓ Ultimaker 2+ will automatically start turning the feeder wheel, through which the filament will be rewind completely.
- ✓ Press "Ready" once it's out.

Loading

- ✓ Place the new spool of filament in the spool holder with the filament in the counter-clockwise direction (the filament comes from the bottom into the feeder).
- ✓ Insert the end of the filament into the bottom of the feeder and push it until the filament is grabbed by the feeder.
- ✓ Wait until the filament reaches the first black bowden tube clip and then press the button to continue.
- ✓ The Ultimaker 2+ will automatically load the filament through the bowden tube, into the print head (the filament is loaded relatively quickly, if it does not load, or is loading very slowly, then something went wrong and it's better to start again).
- ✓ Press the button at the front once the filament comes out of the nozzle.
- ✓ Follow any further instructions on the display.