

Getting started with 3D printing

Introducing powerful ideas through tangible design

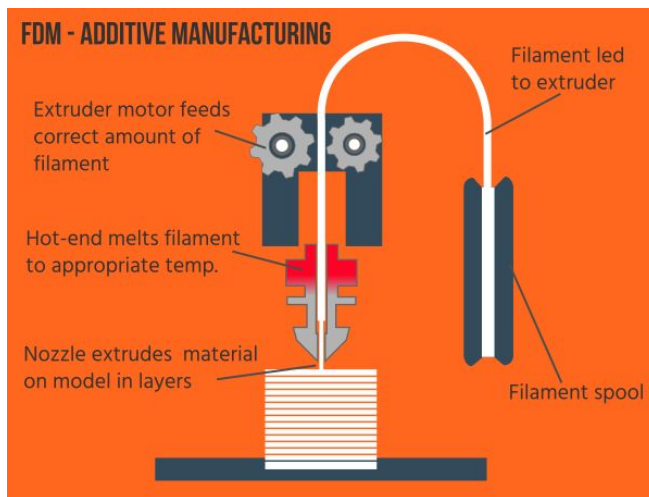
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Introduction

3D printers are slowly but steadily making their way into classrooms and educational institutions, ranging from primary school to universities. The technology provides strong promises of connecting the virtual world with the physical by providing the possibility to see the digital designs created on a computer come to life. However, the road to successfully integrating the technology in the classroom and making the technology a ubiquitous tool for everyone can be daunting. This guide is an attempt to make this journey easier, and to get to the point where powerful ideas can be taught through the most disruptive technology of the 21st century. The process of getting 3D printers up and running always has to involve school managers, teachers and, of course, students. This makes it a task that will always be resource intensive, no matter how much support is given from different areas. However, the pay-off can be immense, and this collection of pages will also include examples of lesson plans that have been tested with great results in classroom settings. During these sessions, the students truly immersed themselves in the projects, and many interesting and profound learning outcomes were observed.

FDM 3D printing

Although several different technologies exist for 3D printing, the one that often finds its way into classrooms are FDM or FFF 3D printers. Other systems such as SLA and SLS are often too expensive or inconvenient for classroom use. FDM 3D printing works by a somewhat simple principle, which is to have a print head moved around, while extruding plastic, thus building objects layer by layer. However, like many simple principles, the specifics of 3D printing can become deviously complicated once one dives down the rabbit hole. Many issues can be had while using this manufacturing method, and many different solutions exist to these. In this section it will not be attempted to go through all aspects of FDM 3D printing, as this is very extensive. Instead vocabulary will be provided for key terms in FDM 3D printing, and other sources will be referred to. The 3D printing community is very active in sharing, which means that extensive quality material can be found online for almost any aspect of FDM 3D printing.



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attempted to go through all aspects of FDM 3D printing, as this is very extensive. Instead vocabulary will be provided for key terms in FDM 3D printing, and other sources will be referred to. The 3D printing community is very active in sharing, which means that extensive quality material can be found online for almost any aspect of FDM 3D printing.

Terminology¹

As 3D printing is still such a new field, the terminology of the industry can sometimes be confusing and even contradictory. Below is a relatively short list of terminology that can help you get started. The list is nowhere near complete, but great online sources exist should run into terms that you are not familiar with.

General:

- **Additive Manufacturing**
 - Additive manufacturing is the process of building up a three-dimensional object, one thin layer at a time. 3D printing is only one category of additive manufacturing, though the two terms are frequently considered to mean the same thing.
- **Computer Aided Design (CAD)**
 - Computer aided design, or CAD, is software that enables users to create models in either two or three dimensional formats. While CAD was initially developed for use in the architecture and manufacturing industries, consumer friendly applications are now readily available for little or no cost.
- **Fused filament fabrication (FFF)**
 - An additive manufacturing technology that is based on the principle of laying down material in layers. It has similarities to the term FDM (fused deposition modelling), however, FDM is a trademark term. Therefore FFF will be used from this point.
- **Filament**
 - The material that is used for 3D printing. It has the shape of a wire and is usually coiled on a spool. Usually consisting of different plastic materials.
- **Polylactic acid (PLA)**
 - A hard, odorless bioplastic that has a low environmental impact. It is derived from renewable, starch-based resources. PLA has a very low shrinkage, which is ideal for 3D models and prototyping at home.
- **Layer resolution**
 - The layer resolution (or layer height) describes the thickness of one layer of the 3D print.
- **Slicing**
 - The process of converting a 3D model, such as an STL file, into a printable file, such as a G-code or F-code. It will divide the model into “slices” so that the 3D printer can build it up layer by layer. Examples of slicers are: Cura, Slic3r, Simplify 3D, and Create it REAL’s own slicer REALvision.

¹ This list has been made with inspiration from the following resources:

<https://ultimaker.com/en/resources/11720-terminology>

<https://www.3dhubs.com/knowledge-base/definitive-3d-printing-glossary>

<https://all3dp.com/1/3d-printing-terms-terminology-glossary/>

File formats

- **STL**
 - A widely used file format for 3D models when 3D printing.
- **G-code**
 - A file format that is used for 3D printing models (after it has been sliced).
- **F-code**
 - A file format used by Create it REAL to achieve high speeds. The F-code is more low level than G-code, enabling certain features in Create it REAL's platform

3D printer

- **Extruder**
 - A common name for the parts that control the extrusion of the filament.
- **Print Head**
 - The part of a 3D printer where material is extruded/jetted from. It is an assembly of multiple components including the nozzle in the case of FFF.
- **Nozzle**
 - The part of a 3D printer where the build material is extruded from.
- **Print Bed / build plate**
 - The print bed or build plate are sometimes used interchangeably. This is a flat surface, that the object is built upon.
- **Bed leveling**
 - Leveling the print bed (sometimes referred to as calibrating) is the process of making sure that the print bed has just the right distance from the nozzle to assure that the object will stick to the bed. Depending on the printer model, this can be more or less automatic.
- **XYZ axis**
 - The 3D printing is in most cases viewed as a cartesian coordinate system, with the X and Y being the plane on which each layer is built, and the Z-axis the height. Exceptions are the Delta and the Bipolar system.
- **Stepper motors**
 - The motors most commonly used to control a 3D printer. A 3D printer will mostly consist of at least four stepper motors, one each axis and one or more used to feed the filament.
- **Controller**
 - A PCB containing controller software and hardware is necessary to run the printer. Create it REAL has developed and manufactured their own mother board, the Bluefin, for controlling a printer. However, different arduino boards are also used for 3D printing.

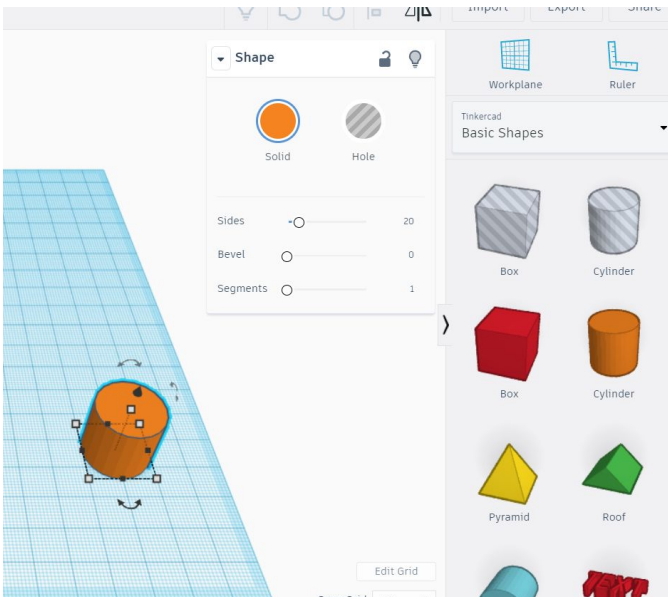
CAD modelling with Tinkercad

Tinkercad is a free, online, CAD modelling software that is easy to learn, but can take you quite far in terms of modelling objects for 3D printing. Tinkercad can also be used to design objects for laser cutting, and it even has minecraft compatibilities.

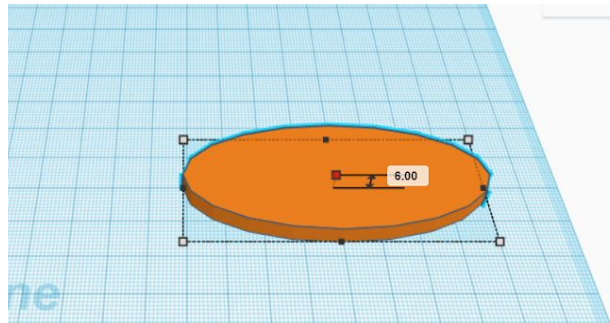
The basic principles of tinkercad is to build any geometry by combining and manipulating predefined shapes. The easy “drag’n’drop” nature of the software entails that it can be taught to young children This is referred to as a CSG modelling tool (more on that later).

Design challenge 1: Name tag

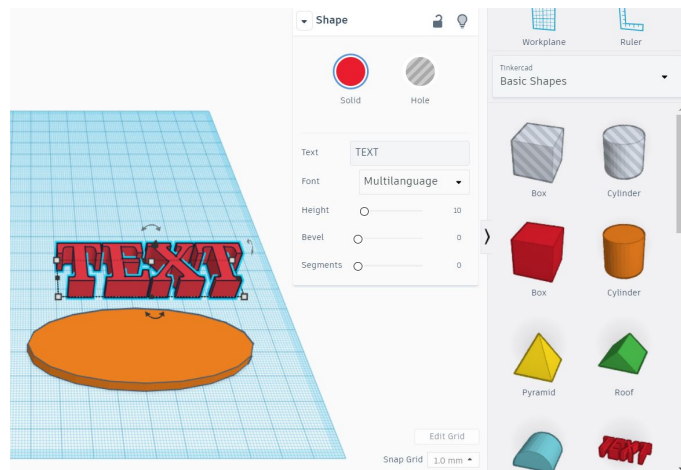
The easiest way to get familiar with tinkercad is simply to design something with it. Therefore we will all be designing a nametag for ourselves to use at these workshops.

Step:	
<p>Step 1: Drag’n’drop in a shape to use for the base of your nametag</p>	

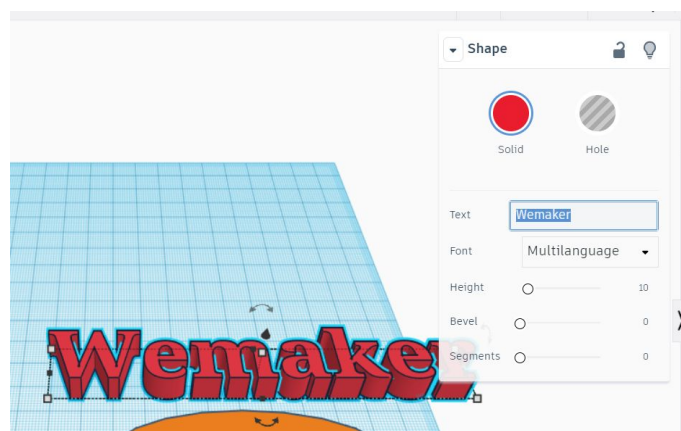
Step 2: Manipulate the shape using the white square widgets on the edges to make it a flat oblong plate



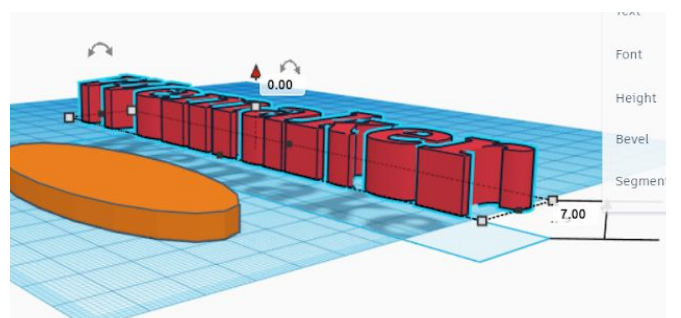
Step 3: Drag in the text editor



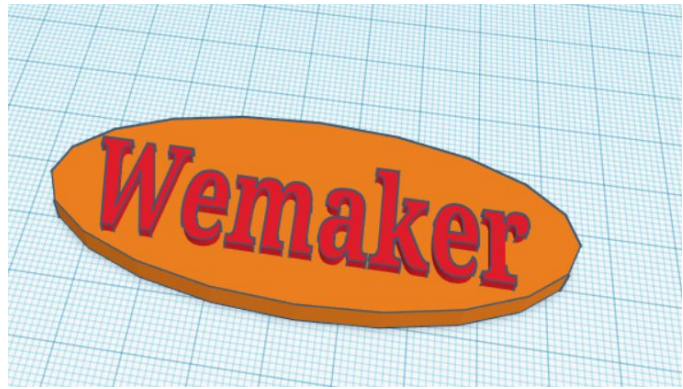
Step 4: Use the “current shape settings window” to write your name. The object will change accordingly



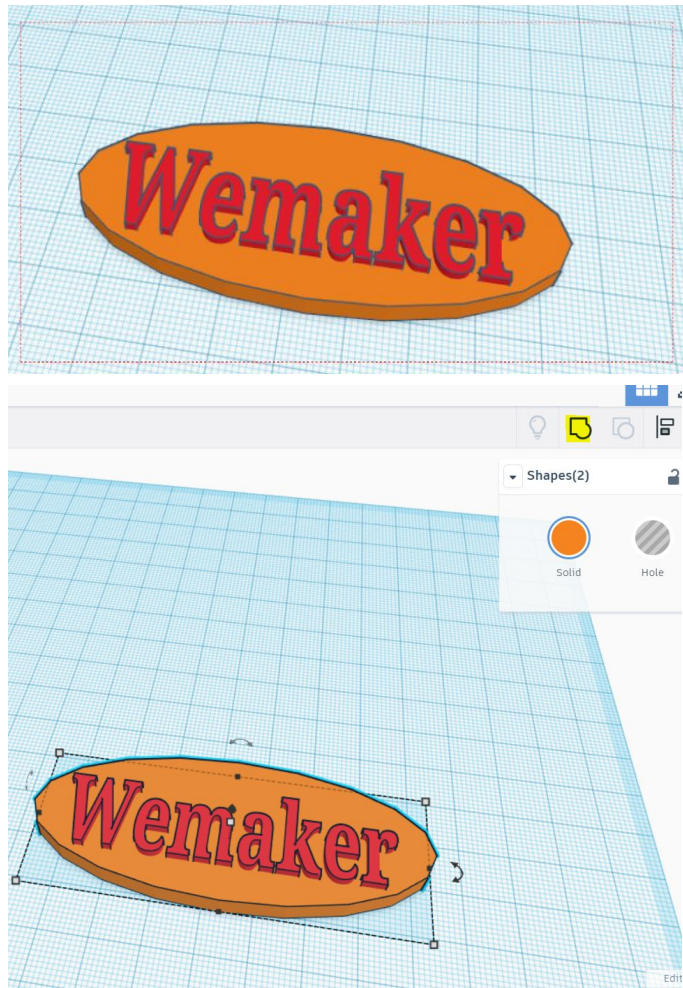
Step 5: Use the top arrow to lift the text up.



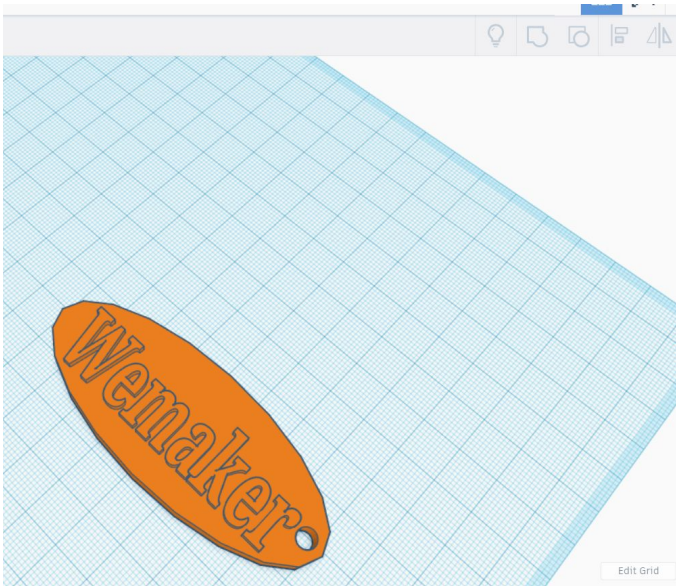
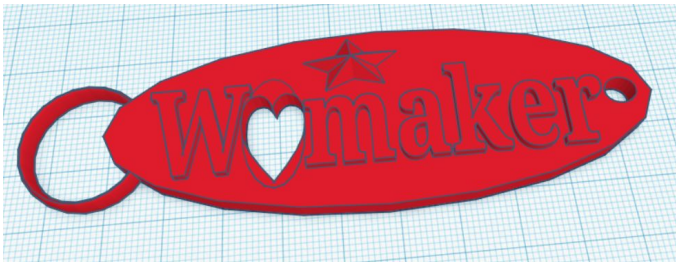
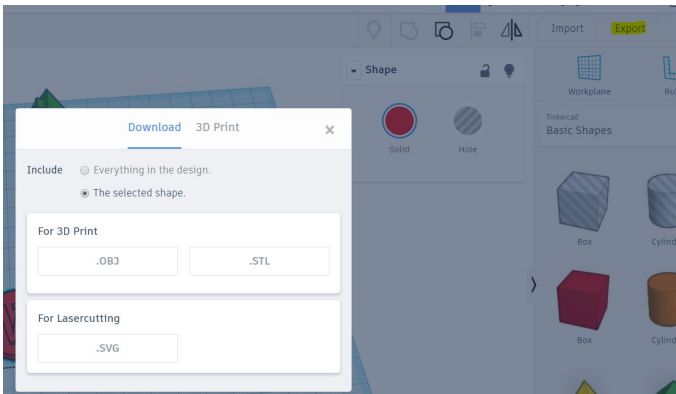
Step 6: Place the text on top of the plate. Once again you can use the widgets to rescale it to the size of the plate.



Step 7: Group the models by selecting both and pressing the group button



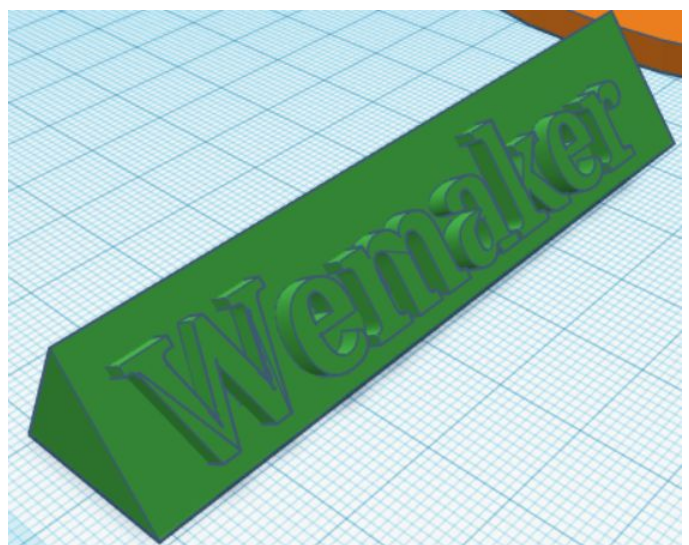
Step 8: Make a round hole in the nametag by dragging in a cylinder, and changing it from “solid” to “hole”. Resize it and place it where you want the hole to be. Group the objects.

	
<p>Step 9: Explore Tinkercad, and decorate your nametag.</p>	
<p>Step 10: When you are ready to print your nametag press the “export” button in the top right corner, and export the model in STL format. You are now ready to print your nametag.</p>	

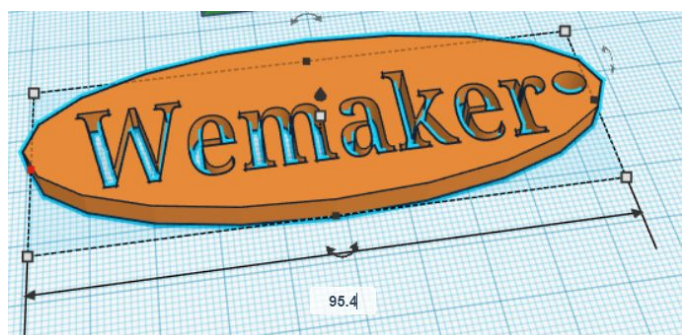
EXTRA 1: Make the text into a hole in the plate instead. Remember that any shape can be converted from a “solid” into a “hole”.



EXTRA 2: Make a wedge shaped nametag. Use the workplane for this.

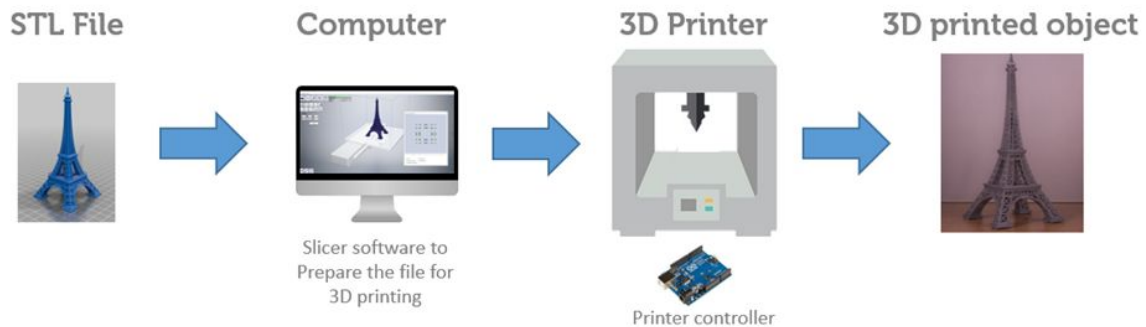


EXTRA 3: make the nametag exactly 95.4mm long.



STL's, Slicers and 3D printing

We have briefly mentioned STL's and slicing previously, but in this section we will dive deeper into the subject, and explore how STL's and slicers work together to produce a 3D printed object. A small chart can be seen below, explaining the steps and order of the process.



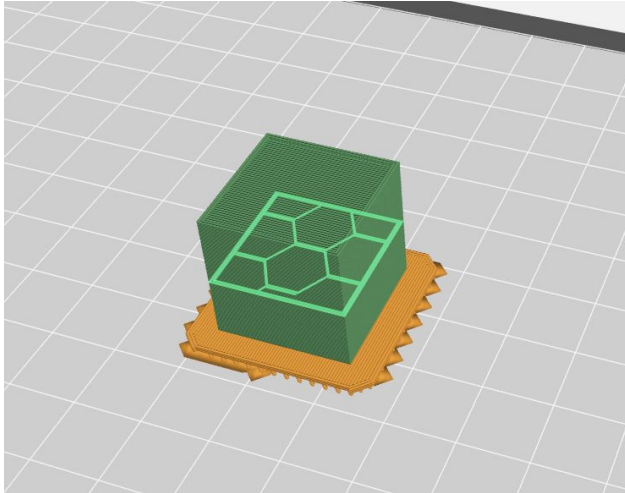
The STL file format represents only the surface of the object. An STL can be produced by most 3D modelling softwares, and is becoming the standard of the 3D printing industry. Also several websites exist with a vast library of STL-files that can be downloaded freely. These websites include:

<https://www.thingiverse.com/> This website was made by Makerbot, and has since been purchased by Stratesys. It features a vast collection of free models, and anyone can upload files directly to the page.

<https://www.myminifactory.com/> A website featuring designs that have been tested for 3D printing. This means that the average quality of the content is quite high.

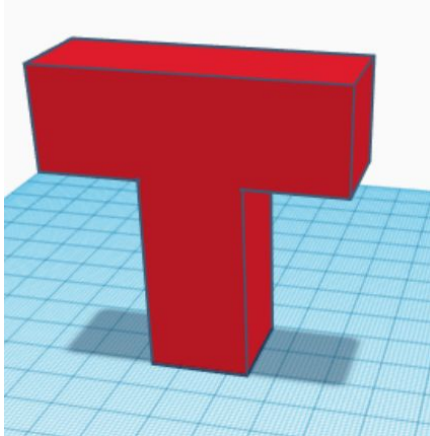
<http://www.yeggi.com/> A website where files can be shared freely but also sold and purchased by designers.

The STL file is often loaded into a slicing software, where it is converted into a file format that relates to the movement and extrusion of the 3D printer (often G-code, or in Create it REAL's case F-code). The slicing software, however, does not necessarily convert the model into a 3D printed object one to one. For instance most 3D printed objects are not solid. This is because the slicer turns the model into an object that has a solid shell, but a partly hollow inner area. Below a picture can be seen of a square, made with hexagonal infill, and an outer shell. Most slicing softwares will also allow you to do certain manipulations of the object, such as, scaling, mirroring, rotating, etc.

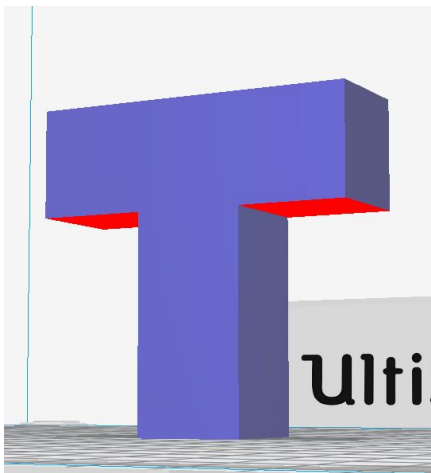


However slicing softwares also have more advanced features, that allows the user to setup detailed specifications for the printer, including how much plastic should be extruded, what the movement speed should be, how the temperatures can be controlled, and much more. Going into the specifics of how to set up a slicer for a printer and a material from scratch is beyond the scope of this session. Instead we will go through the subjects of: infill, support, and outer layers (referred to as “contours” from this point). When teaching these to student we suggest that they are given a design challenge. Front loading students with too much information about the specifics of these things can have a negative impact on the lesson. We have found it a good practice to have the students get their hands dirty, and only after they have been designing and printing something, they can be told about these things, as they can then connect it to their real world experience.

Overhangs

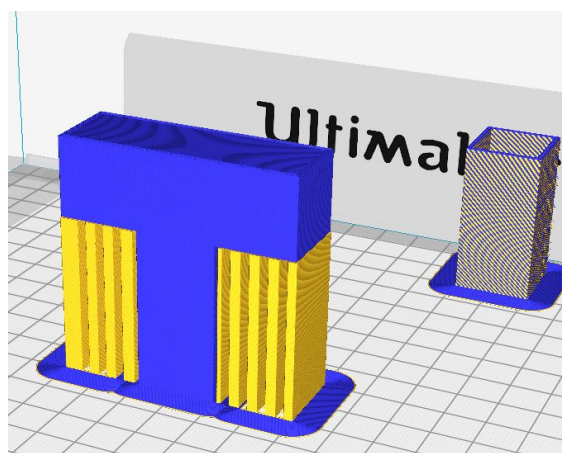
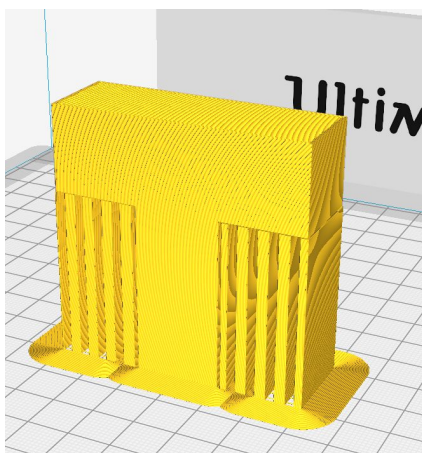


Let us consider the object to the left. It is a shape resembling the letter 'T'. This has an issue in terms of **'Overhangs'**. Overhangs are part of a 3D object that is not supported by layers beneath it. Loading this model into Cura will result in what can be seen below.



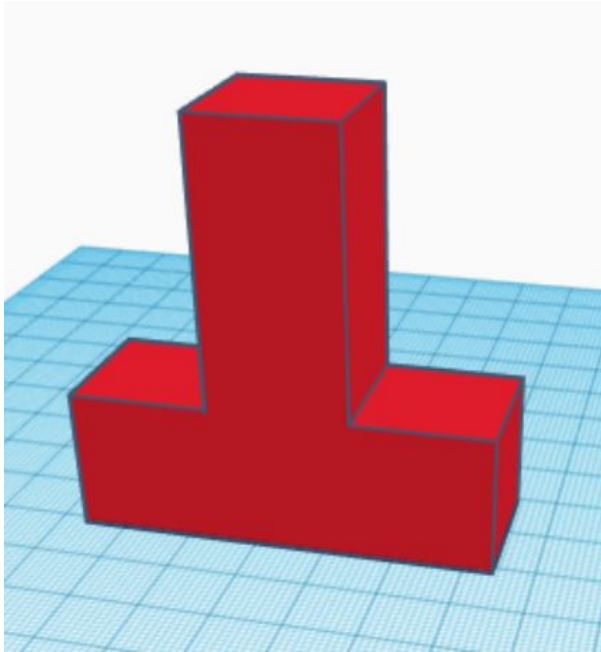
Note that the surfaces beneath the overhangs are coloured red to signify that they are problematic. If the "generate support" check box is then checked, and the model is change to "layer view" the following will appear. This is a rendering of the supports that are generated. Supports is one way of dealing with overhangs, and as can be seen, it simply adds material that can be removed once the print is done. However, support can sometimes be hard to remove, depending on the 3D printer, the filament, and different support parameters. Furthermore, it is wasteful in materials and takes a longer time to print. These can vary greatly from slicer to slicer, and printer to printer. Some printers have the "dual extrusion" option, where one extruder can extrude support material, and the other can extrude, for instance, PLA. Below a screenshot of Cura with the Ultimaker 3 can be seen, and here the supports are printed in a water soluble material. This means that the object can be submerged in water, and the support material will be dissolved over time.

However, with ultimakers recommended settings this object takes 9,5 hours to print



Orientation

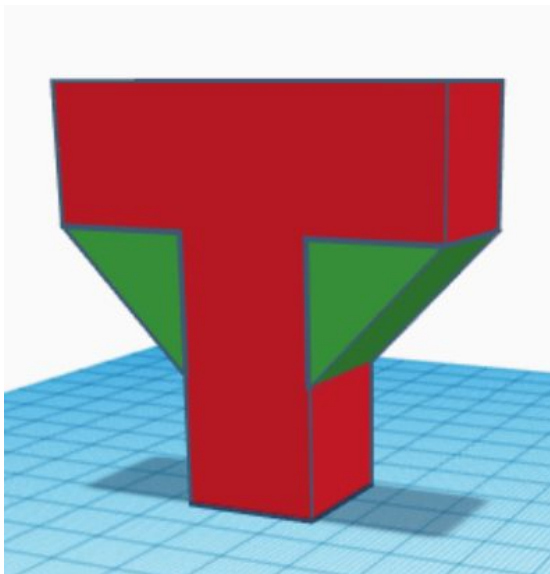
Another way to deal with overhangs is to simply look at the orientation of the model. Some model can in fact simply be flipped on one or more axis, and they will become printable. Usually this is preferable to support, as it does not waste material, and will take a shorter time to print. However, it requires one to think of the 3D printing process, and the fabrication



method. This can be very positive as it is an important aspect within any type of physical design, to consider the production. This field is usually not taught until university, as it is deemed a difficult and advanced topic. However, with 3D printing it can become a natural part of a design process of young children. Flipping a model can usually be done in both the CAD software and the slicing software. In the slicing software, however, the effect of the orientation on the material use, and print time can be observed directly. After designing parts for 3D printing for a while, one usually gets a “sense” for this and will naturally look at a model, and instinctively think of how it can be oriented to minimize or eliminate the need for support.

Smart design

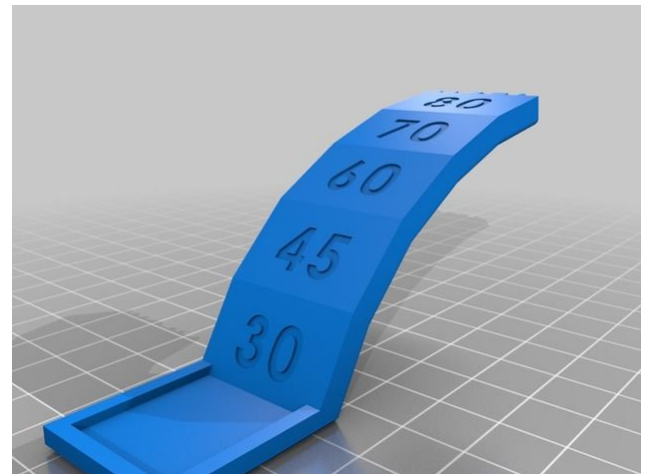
Designing a model, while constantly keeping the 3D printing process in mind, can be



considered the highest level of dealing with overhangs, as one will be designing models with little or no overhangs. As seen on the right the model is altered to accommodate for the overhangs. What is taken advantage of on the picture on the left, is the fact that FFF 3D printers can actually print small overhangs. How good a printer is at printing overhangs will vary greatly, and will depend on: how rapidly the filament can be cooled, how fast the printer is, what material is being used and many other things. Different test prints can be performed to know the performance of each individual printer setup. As mentioned before, smart designing of a part for the limitations of a production method, is very valuable as a

principle, whether the production method is 3D printing, CNC machining, laser cutting or

others. However, for some cases this might distort the original intention of the model. Look at the model above. Will it look like a letter T once it is printed?



Thus, overhangs can be dealt with in a multitude of ways, and in multiple different parts of the 3D printing process. Beneath is a small table showing when the different methods of dealing with overhangs are applied. The bridge lesson, that will be described next, is usually a good lesson to get students familiar with the concept of overhangs. Usually for students who are new to 3D printing, will have the first instinct will be to design the bridge as you see it out in the world. We suggest that students are actually allowed to make mistakes, and print objects even though you as a teacher might know that it will fail. It can often be easier for the student to relate the knowledge of how to deal with overhangs, if they can relate it to an actual experience of seeing a failed print, rather than a long front loaded lesson about it.

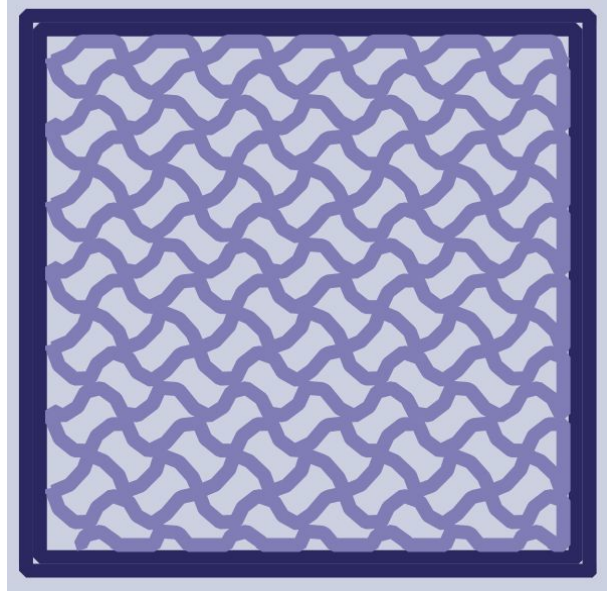
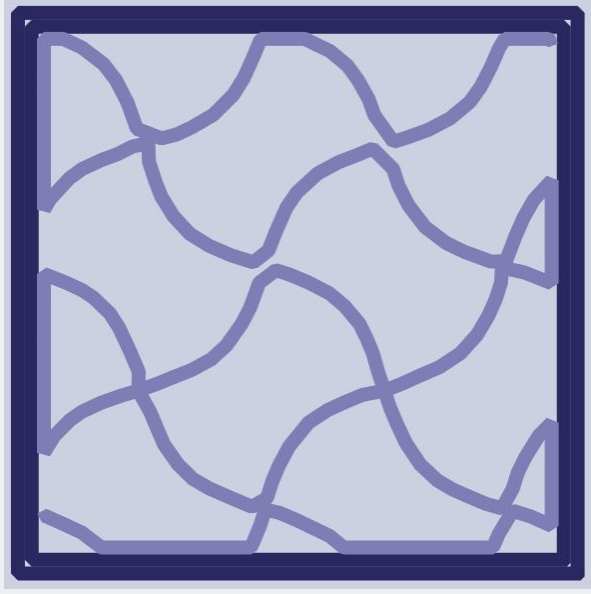
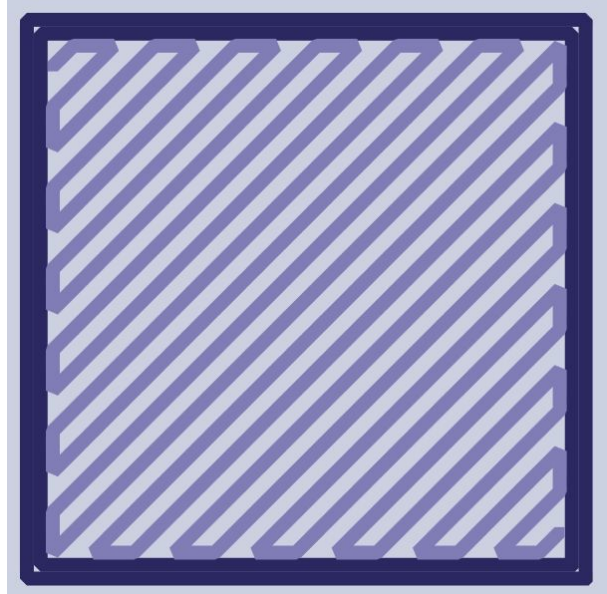
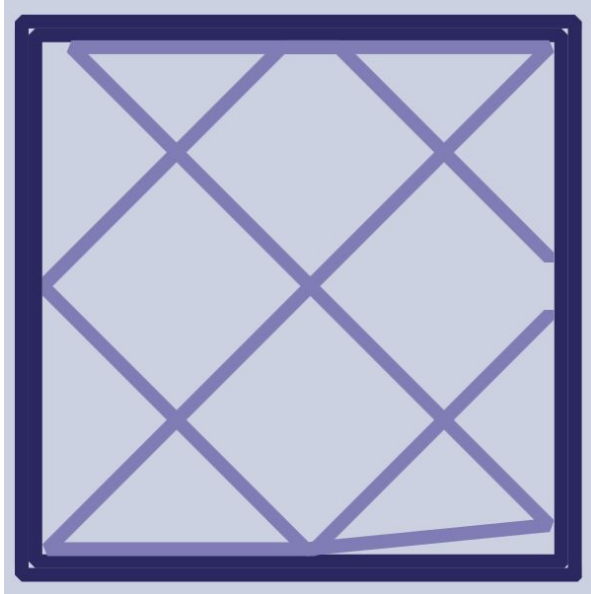
Method	CAD/design SW	Slicer	Post print
Add support	Manual support	Automatic support	Clean up
Change orientation	Design for 3D printers orientation	Flip, and mirror	
Smart design	Designing with 3D printing in mind		

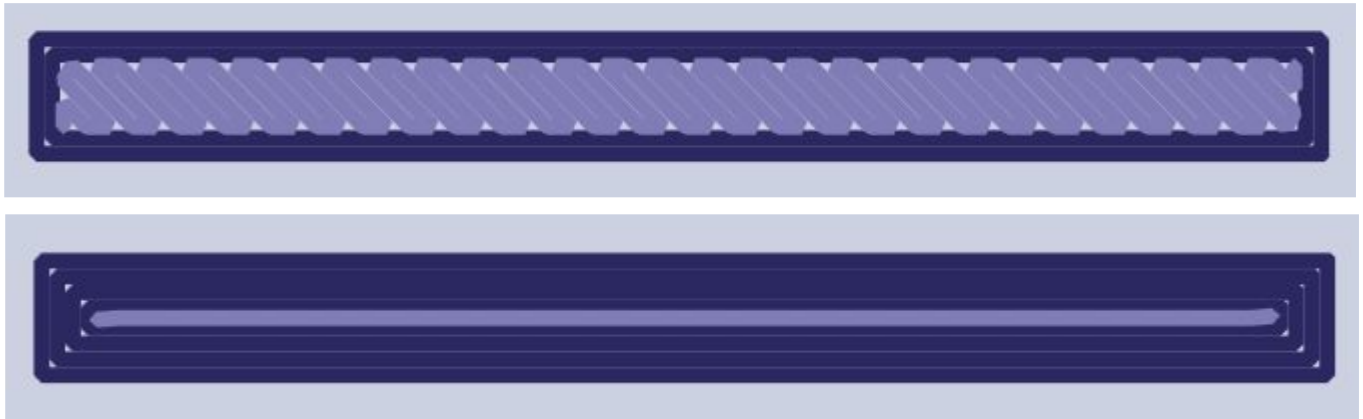
Infill and contours

Mostly 3D printed objects are not printed as a solid, but rather as a shell with a mostly hollow inside. The inside will consist of a structure of printed material, referred to as infill. In the slicing software the density of this infill can usually be controlled. The default infill is normally around 20% meaning that 20% of the internal geometry of the object will consist of plastic,

whereas the remaining 80% will be hollow pockets of air. For objects that do not require significant structural integrity this is usually sufficient. However, the infill density can be increased to acquire higher strength. The tradeoff is that this increases material use and printing time.

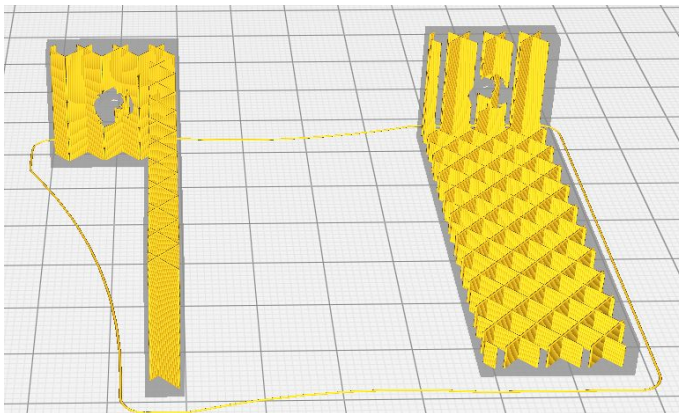
Several different infill types exist. The most common, and one of the most simple, is the square infill. However, other infill types exist that can give the object interesting properties. Below we see an example of the square infill at 15% and 50%, and the Gyroid infill at 15% and 50%. The Gyroid has many interesting properties, and Anca will be happy to answer any questions you have about this and other infill types.

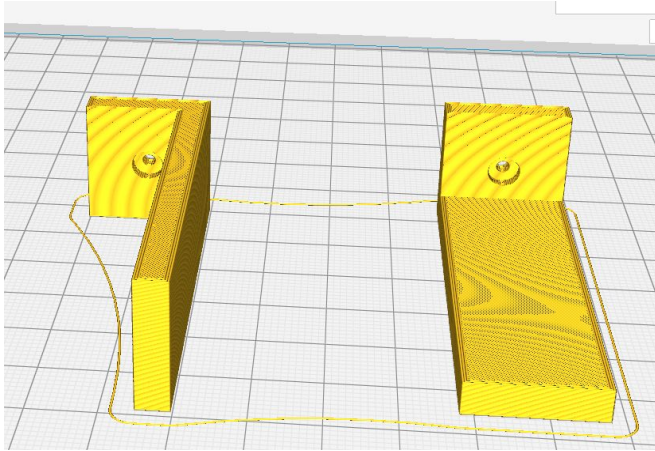




However, the infill is not the only determinant of the strength of an object. The outer shell, or the amount of contours, can also have a big influence on how strong an object is. Above a single slice of the same object can be seen. The only difference between the two is that the bottom object is sliced with 4 contours while the top object is sliced with 2 contours. The increased amount of contours can actually increase the strength quite a lot.

Below an example of a very simple bracket can be seen in Cura, on the top picture only the infill is shown, and on the bottom picture the shell can be seen. As you might have noticed the bracket is shown in two different orientations. The question is, will the bracket be equally strong in each case? This actually depends on what we mean with strength, as the next example will show.

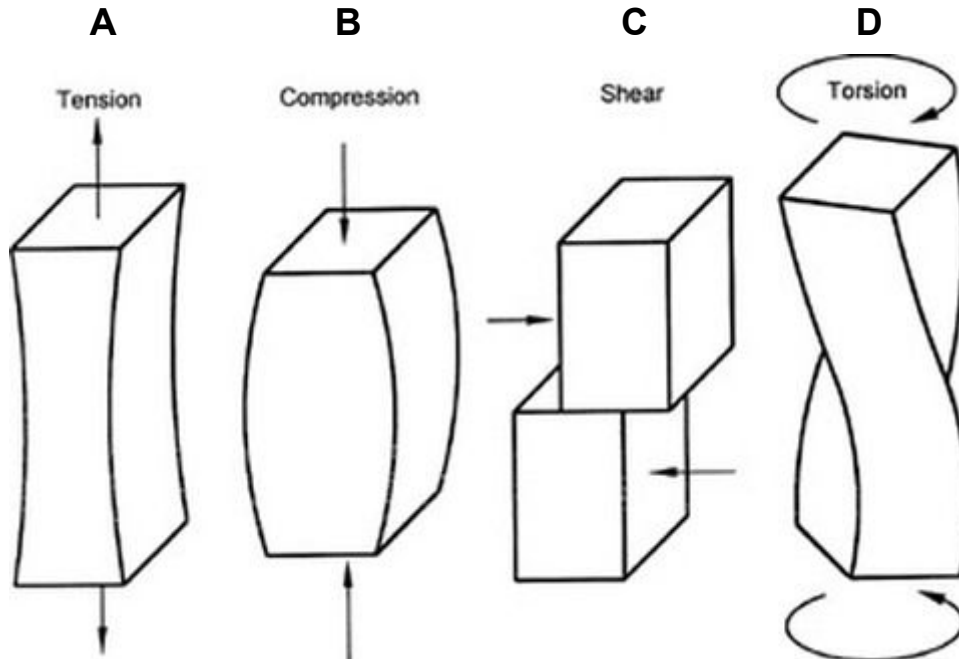




Drawing challenge: strength types and 3D printing

Look at the drawing below. It is a representation of 4 different kinds of strength that an object can have in the field of structural engineering: tensile strength, compressive strength, shear strength, and torsion strength. In this small exercise you will make a qualified guess on which orientation will result in the highest of each of these types of strength.

Assignment 1: Draw the layers of the 3D printed objects on the drawings below, in the orientation you believe will result in the highest of each type of strength.



Assignment 2: Of each of the examples which one would you think benefits most from high infill percentage, and which would you think benefits most from a thick shell of many contours? Mark the ones you think below with an X.

	High infill percentage	Thick shell / many contours
A		
B		
C		
D		

We will discuss the results in class afterwards.

The fact that a 3D printed object is not equally strong on all sides is referred to as “Anisotropic”. This property comes from the very process of 3D printing, which is to build objects by layers. This leaves the adhesion between the layers as a limiting factor strength wise. This is why, in the above example, the strength is always highest, when the forces move opposite to the layers, along the shell. This is worth considering when designing and printing an object in which strength is desired. For more reading about this we refer to “the 3D printing handbook”². For these simple figures, the optimal strength for a specific part can often be found using the options of the slicer software. However, for more complex parts that might need different types of strength in different areas, one will have to think of these things already during the CAD modelling. Here will follow an example of a simple lesson plan, that can be given to student of various ages, that will let them explore this in an intuitive manner.

Design challenge 2: A highway bridge

This is a design challenge that has been tested in a real teaching situation at one of our partner schools. It is a good introduction to the basic slicer settings of a 3D print, since the participants will often discover subjects like overhangs, infill and contour by their own accord, and while working on a project. The lesson plan is also well suited for group work, and can easily be modified to increase or decrease complexity, making it suitable for a wide age group.

Design prompt:

The [Danish/Romanian/Italian/French/Greek] ministry of logistics and transportation has assessed that many of the bridges over highways in the country are worn down, and will need replacement immediately. They are looking for a contractor that can provide them with a bridge that uses little material, but also one that is strong. In this assignment your team will be the contractor and will design a scale model of the bridges that can convince the bridge committee that your design is the best choice.

² <https://www.3dhubs.com/3d-printing-handbook>

Requirements:

- You will design a model of the bridge in scale 1:500.
- The bridge has to accommodate 4 trucks driving below it, and two cars driving on it.
- You will calculate the material cost of the bridge, knowing that one m^3 of reinforced concrete costs 210€
- You will test the strength of the bridge by gradually placing weights on top of the bridge until it breaks. You will then note down the weight at which the bridge broke, and this will be the measure of the strength.
- You will then redesign your bridge based on your experience with the previous bridge, thus improving the design through several iterations.

Design and printing

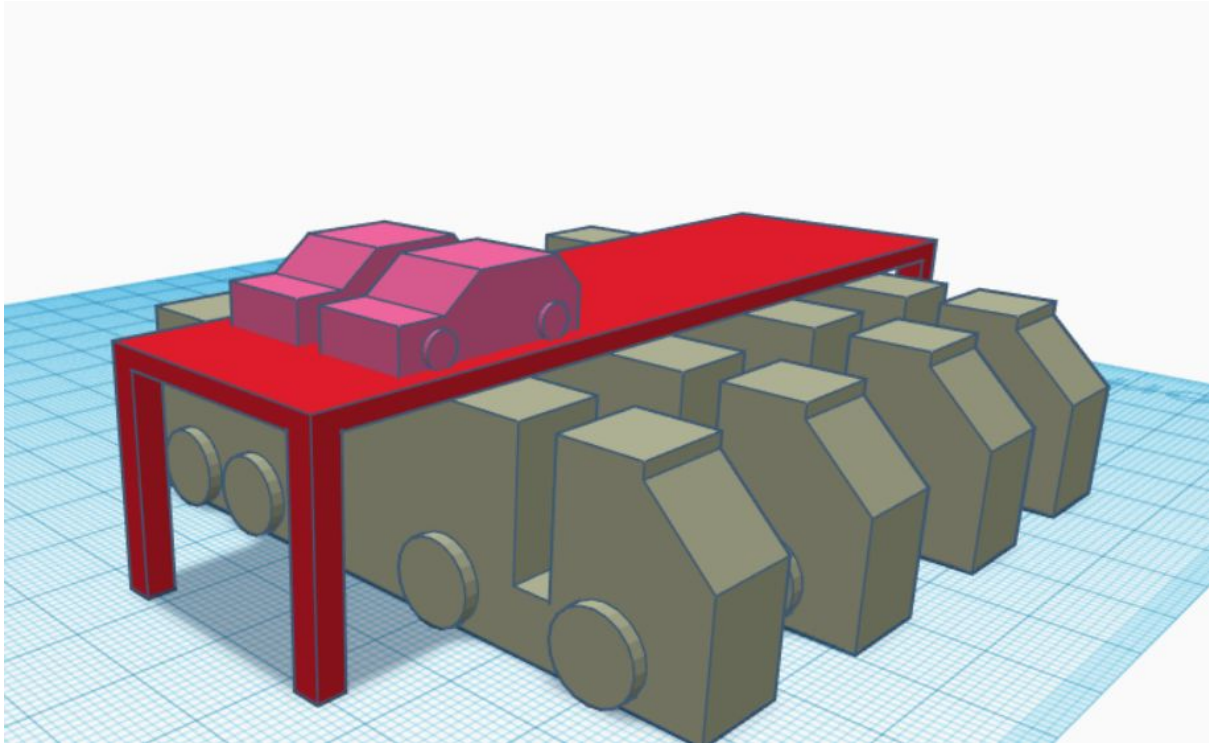
You will be designing your bridge in Tinkercad, which you should be familiar with by now. However, some features in Tinkercad can be good to mention for this part. Refer to the Tinkercad cheat sheet to find these functionalities.

Import: Use this to import the car.stl and truck.stl. These are scale model of real life cars and trucks that you can use to design your bridge around. Remember that the bridge has to accommodate four trucks below and two cars above.

Align: The align function can be used to align one or more models with each other. This can be relevant for this project as it makes precision modeling easier.

Workplane: A new workplane can be inserted making it easier to build models on top of each other. A workplane can even be added to the side of a model.

Once a bridge model has been created, download the STL file and load it into REALvision. We recommend that you get your first model printed quite fast, so you can achieve several iterations.



When running the model through the slicer, remember what the most efficient way to deal with overhangs is.

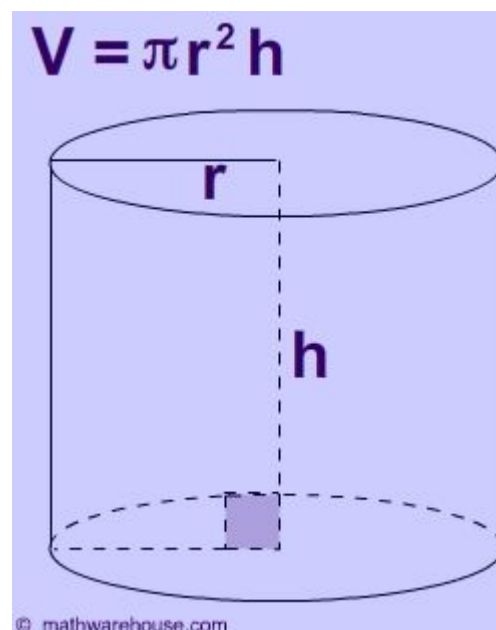
Calculations and measurements

For each bridge you design and 3D print you will have to extract two factors: The **price** of raw materials, and the **strength** of the model. The price you will obtain through calculations, and the strength will be obtained through experimentation.

Price

In the slicing software you will usually be able to obtain information about the filament consumption. This can either be given in meters of filament, or grams of filament.

Remember that filament is usually a long cylinder with a given diameter (in this workshop the diameter is 1,75mm, but 2,85 is also used). Using the equation for obtaining the volume of a



cylinder from its radius (**r**) and its height (**h**), you can obtain the volume of material used for the model. Remember now that the model is designed in a scale (**s**) of 1:500. Finally remember that the price (**p**) of one square meter of reinforced concrete was 210€. Note also that the diameter of the filament is provided in mm, while the length of the filament is in m. It can be an advantage to convert all units into meters. Below is the equation that can be used for this calculation:

$$Price = \pi \cdot r^2 \cdot h \cdot s^3 \cdot p$$

Once the price has been calculated write it down on a post-it note. The price of the bridge can be calculated while the first bridge is printing.

Strength

Once the bridge has been printed the strength of the bridge will have to be tested. This is done by putting stacks of papers on top of the bridge, gradually increasing the weight, until the bridge collapses. Note down how many stacks of paper the bridge could support. This will be our measure for strength in this lesson. Also write this down on the same post-it note.



Self assessment and reflexion

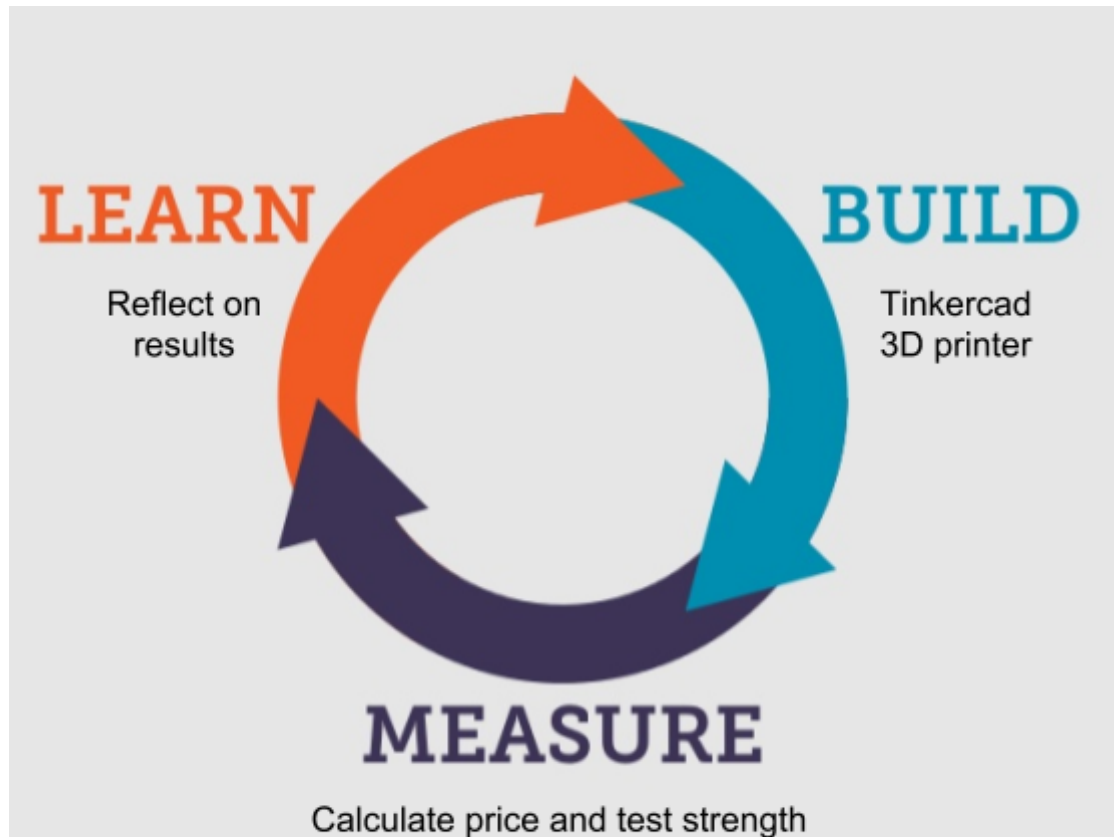
Once the bridge has been designed, the price has been calculated, and the strength has been tested, we will now use an assessment tool dubbed the “Oresmian Coordinate system”. This is a coordinate system made up of two axes, relating to the two factors we were interested in: Price, and strength. You will place your design on top of your post-it at the corresponding areas in the coordinate system. The coordinate system can help you plan the next iteration of your bridge.

You can now debate the following questions:

1. Where is the optimal design in this coordinate system?
2. Why do you think your bridge is placed where it is?
3. Compare your position with that of your competition. What is the greatest strengths and weaknesses of your design?
4. How can you improve your design?

When you have debated these questions in your group go back to the drawing board! Design a second iteration of your bridge that is better on at least one axis. Look at where your bridge broke and use this knowledge to your advantage.

Continue with this process and go through as many iterations you have time for.



How to balance structure and freedom in a project

The example above example of a lesson plan is an attempt to strike the perfect balance between freedom and structure in a lesson. 3D printing as a technology is deeply ingrained into the “maker movement”, and the philosophy of this movement is beginning to influence how we teach technology in schools. The maker movement advocates free access to powerful technologies and a community mindset of helping each other out while learning new technologies and skills, rather than relying on established, sometimes rigorous educational institutions. However, when educational institutions adopt this philosophy, it becomes necessary to look at these two movements and take the best from both worlds.

Our research at the local schools identified that teachers prefer to have some structure in their lessons. This chapter will focus on how to unite the teachers’ desire to have some structure with the maker movement’s philosophy of self directed learning and tinkering.

What does the literature say?

Most people involved with educational technology will be familiar with the works of Seymour Papert. A student of Piaget, as well as a mathematician, Papert wrote books like “Mindstorms”, and “The Childrens’ Machine” which lay the grounds for his theory of “constructionism”.

Constructionism is a further development of Piaget’s Constructivism: the notion that children construct knowledge through direct experience rather than getting knowledge transmitted from a book or a teacher. Papert’s constructionism adds to this theory that the construction of knowledge by children happens best in situations where they construct personally meaningful objects, whether it be a poem, a robot, a computer program or something else. Papert’s work was centered around the computer and programming (this is what he refers to as the “childrens’ machine” in the book of the same name). Although, Papert never specifically addressed 3D printers (mostly because the desktop 3D printer as we know it today was not invented at the time he was active within the field) his theories on teaching and pedagogy are widely applicable to this technology.

One of the concepts that Papert introduced, that can be applied here, is the concept of a “microworld”. This refers to a learning environment where powerful and seemingly complex ideas can be explored in a natural and explorative way. Papert introduces one such microworld for learning newtonian physics, a subject that is often very hard to grasp for beginners. Papert suggests that the reason for this is the fact that newtonian physics are always introduced directly through the mathematical equations that are used to describe them. As an alternative approach Papert developed a microworld where children could program different elements that would in term act through the laws of newtonian physics. This will mean that children can have a more natural and intuitive grasp of the concept of

newtonian physics without the need for involving the formal math. Papert argues that although the child never sees an equation through this process, the child will have a much easier time to relate to the formal equations once they are introduced at a later point, because they will be able to connect it through a quite different experience.

Sylvia Martinez in her book “Invent to learn - Making, Tinkering, and Engineering in the Classroom” assesses many aspects of the maker philosophy in the educational field. One of these is the topic of “what makes a good project”. She defines the following eight characteristics. We will attempt to briefly explain how the bridge project can support these aspects.

1. **Purpose and Relevance** - The children are working on a problem that is very close to real world problems.
2. **Time** - It is important to set aside enough time for this project. About five hours is necessary, even with fast 3D printers. This is because the children should be achieving several iterations of their design.
3. **Complexity** - This project can introduce the concept of finite analysis and construction techniques depending on the level of the students.
4. **Intensity** - We see that children can become completely immersed in the design of these bridges, and we have even had students finding lunch breaks extremely annoying and inconvenient for their workflow.
5. **Connection** - The connection between the group members in this project is one of the more obvious ways teamwork and collaboration is taught in this lesson. What was unexpected was that we saw students help each other from between different groups, and even different grade levels and classes, to perform a good strength test.
6. **Access** - We planned the activity so each group of 3-4 students had their own 3D printer. This meant that they could plan the printing process themselves. The students slowly became masters of time management, and would redesign bridges that took too long to print, and be allowed to have breaks when a print was started, and calculations had been performed for the design.
7. **Shareability** - The Oresmian coordinate system makes the lesson shareable. All students can see other students work, and compare their own progress to others.
8. **Novelty** - While working on this project, the students receive only a brief design prompt describing the aim of their design, and what parameters it should perform well on. From then on they discover for themselves. We have seen students begin to implement cross beams and arch designs, both practices of structural engineering, without ever being explained these concepts by a teacher.

Keeping the design prompt short is also described by Martinez as a good practice of a project. In this case the prompt can be very short. The aim is quite simple and can easily be explained fast. A quick demonstration of the strength test, preferably with a very flimsy bridge, can suffice to explain how this is done. From here the explanation of the calculation can in fact be the most time consuming part, although this can actually be done ad hoc with

decent results. Make sure that the student begins to design fast. The learning comes from the iterations of the bridge, and the direct experiences involved in this.

In this regard, our bridge project is an attempt of creating a project or a microworld for the teaching of structural engineering, but through an open ended, but yet directed, design prompt. Children as young as 10 years will be gaining knowledge about finite analysis and construction techniques, normally not taught until university level of mechanical engineering, architecture or similar fields. They are not studying the formal equations use, but are instead gaining the intuitive Piagean learning experience. They will encode the information about what makes a bridge strong, with the experience of gradually stacking weights on top of the bridge that they designed themselves, and with eager anticipation look for and listen to when the bridge slowly gives in, and then suddenly collapses completely.

We have found through our experience that the children delight in the process of breaking their bridge. After all, how often are you allow to break things on purpose in school? This also teaches the children a deeper lesson still, failure is sometimes necessary to learn. Their bridge not only should fail, but must. Because if the bridge is not pushed to its breaking point we will not know how to improve it for the next iteration. But the lesson also forces them to reflect on the destruction they bring upon their design. It is not merely destruction for the fun of it, as one might see when a child builds a sand castle, only to kick it a few minutes later. They are forced to carefully inspect the damage they have done to their bridge, and transform what they discover into a new tangible design, that can be re-tested again in this iterative process.

The Oresmian Coordinate system

The idea of free project based learning activities is not new, and even Papert's ideas from the 80's are based on the even older ideas of John Dewey and Marie Montessori. One thing that we claim, with some hesitation, to be a novel invention is that of the Oresmian Coordinate system³. Strictly speaking, this need not to be more that two stripes of painter's tape, with units and scale written on them. However, the effect of this teaching aid is seen to be more profound. The coordinate system makes the iterative nature of the design process more visible. You can see the mistakes you made in one version, and understand how this changed the performance in the other versions. The coordinate system provides a great opportunity for a discussion with the students about their design, as well as provide feedback and question their process, in order to make the students think about their future iterations. The Oresmian Coordinate System can also be used in several other lessons, as long as there is at least two parameters an object can perform on. We will briefly cover a few now:

3

[http://vbn.aau.dk/da/publications/barriers-and-opportunities-for-3d-printing-in-danish-schools\(e6029340-0c6d-43f8-85e9-5f62c8bd6578\).html](http://vbn.aau.dk/da/publications/barriers-and-opportunities-for-3d-printing-in-danish-schools(e6029340-0c6d-43f8-85e9-5f62c8bd6578).html)

Boats

The children can take inspiration from the following design on thingiverse:

<https://www.thingiverse.com/thing:843646>

They can then redesign several of the components to achieve the boat that can go the furthest, but also carry the most weight (in terms of for instance coins). They will here explore subjects like: Hydrodynamics, friction, Archimedes' principle, and center of gravity.

Catapult

The students design catapults that can fling a predefined object as far as possible and as precise as possible. Thus, the students will have to design a catapult that both has raw power to shoot far, and also the precision to hit within a target. Therefore, both axes of the coordinate system will have a unit of length (distance traveled, and distance from target). The catapult can consist of many parts, a frame, an arm, a spring and many others. All these can be redesigned individually to achieve the best result. Through this, the students can learn about: ballistics, parabolic curves, the scale and lever principle as well as designing a system consisting of multiple parts, thus forcing them to think of the whole system in a holistic way.

Spinning top

A spinning top that can be started by a gear has been a popular toy for many years. You can find a fully 3D printable version of this online: <https://www.thingiverse.com/thing:1395135>

The advantage of this design is that most of the parts can be printed in advance before the lesson even starts. During the lesson the students can then focus on redeveloping and improving only a few key parts of the design. The students can use the Oresmian Coordinate System to plot the weight or diameter and the average spinning time of the spinning top. In this lesson the children will touch upon: inertia, momentum, newtonian physics, and Euler coordinates.

Summary

This manual has been a quick guide on how to get started with 3D printing in the classroom. It is in no way a complete guide, as such could most likely never exist. 3D printing is an ever developing field, and the technologies that we teach the children now will without doubt be outdated once they start their careers. Therefore, it is important to realise that the sustainable lessons comes not from teaching children how to 3D model and 3D print, but to teach entirely other things through the use of this technology. Teaching students that a design is never final, that things can be improved through iterations, that it is necessary to fail to learn sometimes are all examples of life lessons rather than 3D printing lessons. By focussing on the big picture and on what one wants to achieve with 3D printing, rather than

getting lost in the specifics of slicing and print quality, can mean that students learn powerful ideas that can last them a lifetime. The unique possibility of the 3D printer is to see one's ideas come to life before your eyes and being able to test them in real life. The possibilities of this technology are nowhere near understood yet, but we firmly believe that the truly amazing uses of the technology will come not from the minds of our generation, but of the generation we teach.



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3D printing in general

The 3D printing Handbook <https://www.3dhubs.com/3d-printing-handbook>

Simplify3D has a guide for both print quality, and materials

<https://www.simplify3d.com/support/materials-guide/>

<https://www.simplify3d.com/support/print-quality-troubleshooting/>

Technology in education, and makerspaces

Invent to Learn: Making, Tinkering, and Engineering in the Classroom, *Sylvia Martinez and Gary Stager* <https://inventtolearn.com/>

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