

## 3D Printers - How Do They Work?

The topic of 3D printing has peaked your interest? Have you tried to find information on this vast subject, but got lost either in a multitude of 3D printing news only sites, or short and/or superficial articles? Are you still trying to get your head around the ins and outs of 3D printing technology?

If you answered yes to any of the above questions, you are not alone! 3D printing can be complex to take in initially, as the learning curve may be quite steep. We know the feeling since we have been there ourselves. But, do not despair, we have written this article to explain 3D printing technology with the beginner in mind. To make all of this easy to understand, we have added quite a few pictures and illustrations. Hope you enjoy the read!

### Starting assumptions:

This article only looks at Fused Filament Fabrication printers (FFF), also known as Fused Deposition Modelling (FDM) printers or Molten Polymer Deposition (MPD) printers. We will not discuss any of the other 3D printing technologies, like Digital Light Projection (DLP), Stereolithography (SLA) and Selective Laser Sintering (SLS), etc. The reason is simply that FFF printers are by far the most common 3D printer type used for home 3D printing, i.e. desktop 3D printers. If you are considering to buy your own 3D printer, a FFF is most likely the 3D printing technology that you will end up using. Note that FFF is a synonym of Fused Deposition Modelling (FDM) - both terms describe exactly the same technique. However, Fused Deposition Modelling and its abbreviation FDM are trademarked by Stratasys Inc, one of the major 3D printing companies.

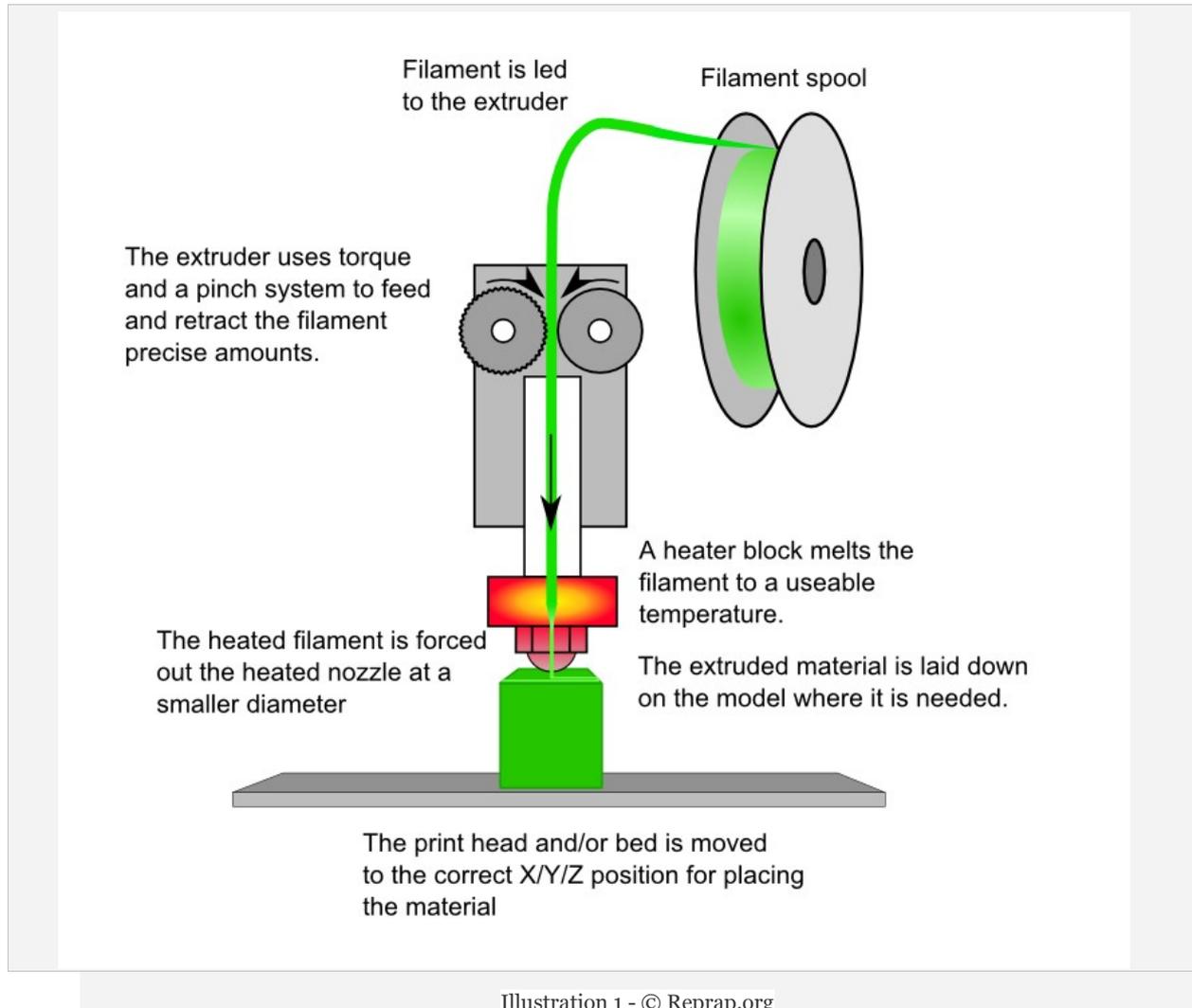
We use our Ultimaker 3D printer (note: it is an Ultimaker Original, not the newer version called the Ultimaker 2) as a reference throughout this article. Although the Ultimaker's working principles do not differ fundamentally, it should be noted that other printers models may look somewhat different. However, the functioning principles of all FFF printers are largely the same.

## What is Fused Filament Fabrication (FFF)?

Fused Filament Fabrication is nothing but a fancy word to describe a process by which a machine deposits a filament (picture something like a small string) of a certain material (normally thermoplastics, wax or similar products) on top or next to the same material, in order to create a joint by heat and/or adhesion. Thermoplastics are plastics which become semi-liquid above a specific temperature and return to a solid state when cooling down.

A FFF printer prints a 3-dimensional object by extruding a stream of heated or melted thermoplastic material, which is carefully positioned into layer upon layer, working from the bottom up. Just imagine a heated print head that is oozing out a permanent flow of molten plastic onto a surface in order to form, through multiple layers, the virtual object you chose to print. By adding layer upon layer, which will almost immediately harden upon leaving the hot print head, you will see the object that you chose to create materialize right in front of you.

Just have a look at **Illustration 1**, which gives you a clear understanding of FFF.



## Working in 3 Dimensions - Working Principles of Linear Robots

In order to be able to print a physical object, i.e. an object in 3 dimensions, a 3D printer needs to be able to move on 3 coordinate axes (i.e. most commonly referred to as length, width and height).

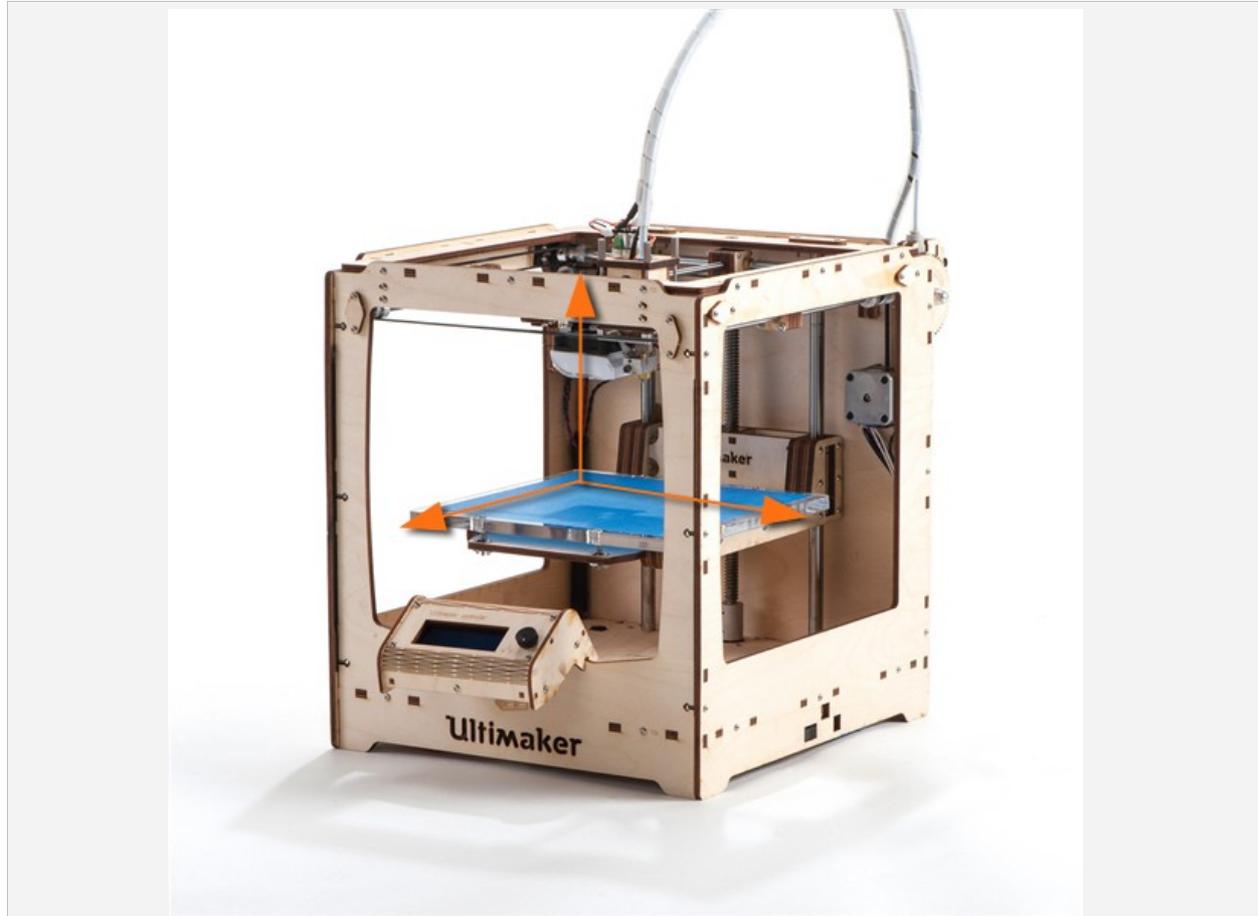


Illustration 2 - © 3Dprintingforbeginners.com

But how do you tell the machine where to put its nozzle at a specific moment? Mathematicians generally refer to the term of "Cartesian coordinate system" in order to specify the position of a given point in 3-dimensional space. But don't worry, we are not going to do any maths here. Just have a look at **Illustration 3** in order to understand what is meant by this. The general convention is to use the X, Y and Z axes in order to map a specific point in a 3D coordinate system.

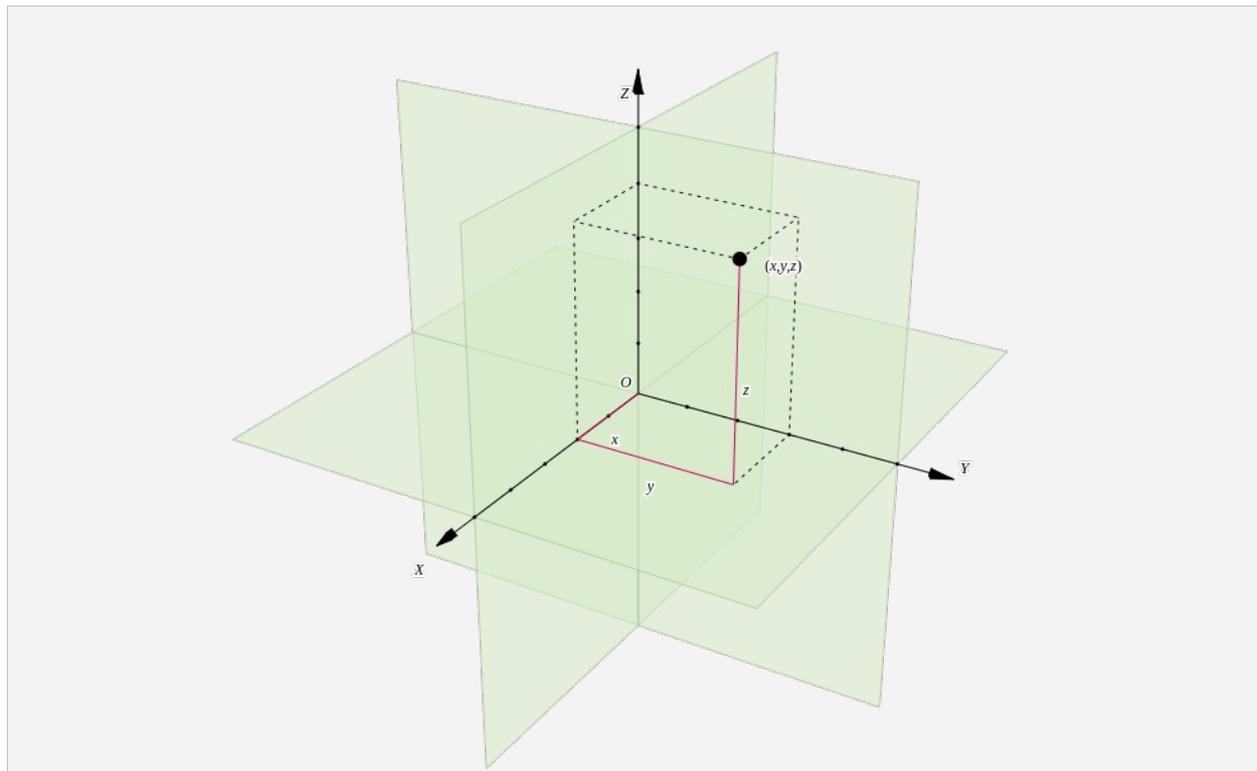


Illustration 3  
Cartesian coordinate system

If thinking in 3 dimensions may seem confusing in the beginning, just think about 2 dimensions to start out. Remember how your inkjet printer used to work? It used only 2 dimensions, i.e. the X and Y axis and may therefore help you understand the process. Once you had finished typing your document, the computer translated the document into coordinates for your printer. A moving head printed the letters on paper, usually on one fixed axis (going from left to right and back - i.e. the horizontal axis) while little motors drove wheels which advanced the paper page on the other axis (up and down - i.e. the vertical axis). The principles are the same for a 3D printer, except that it is able to move in one more direction (depth) and thus is able to physically print objects.

Nearly every 3D printer is built around the principle that its 3 principal axes are linear. This means that their axes are at right angles to each other and that they move in straight lines (that is: they do not rotate). Machines which use this principle are known as linear robots or cartesian coordinate robots, as opposed to Delta- or Polar-type robots. Typical examples of linear robots are 3D printers, but also computer numerical control (CNC) machines.

In order to move along these 3 axes, 3D printers generally make use of fixed rods, timing belts and pulleys, in order to manoeuvre the print head(s) and or the print platform to the exact position needed. These timing belts and pulleys are connected to small motors, which are generally referred to as "stepper motors" (**Illustration 4**). These relatively small motors permit extremely precise movements, often in the vicinity of a fraction of a millimetre. The stepper motors form an important part of any printer, as they are in a great part responsible for the quality of your print, i.e. a cheap stepper motor is not able to realise the same accuracy as more expensive models. Also, when working, they tend to make

quite some noise and cheap stepper motors can be especially noisy. However, more recent models have been addressing this particular issue and are far quieter than the older models.

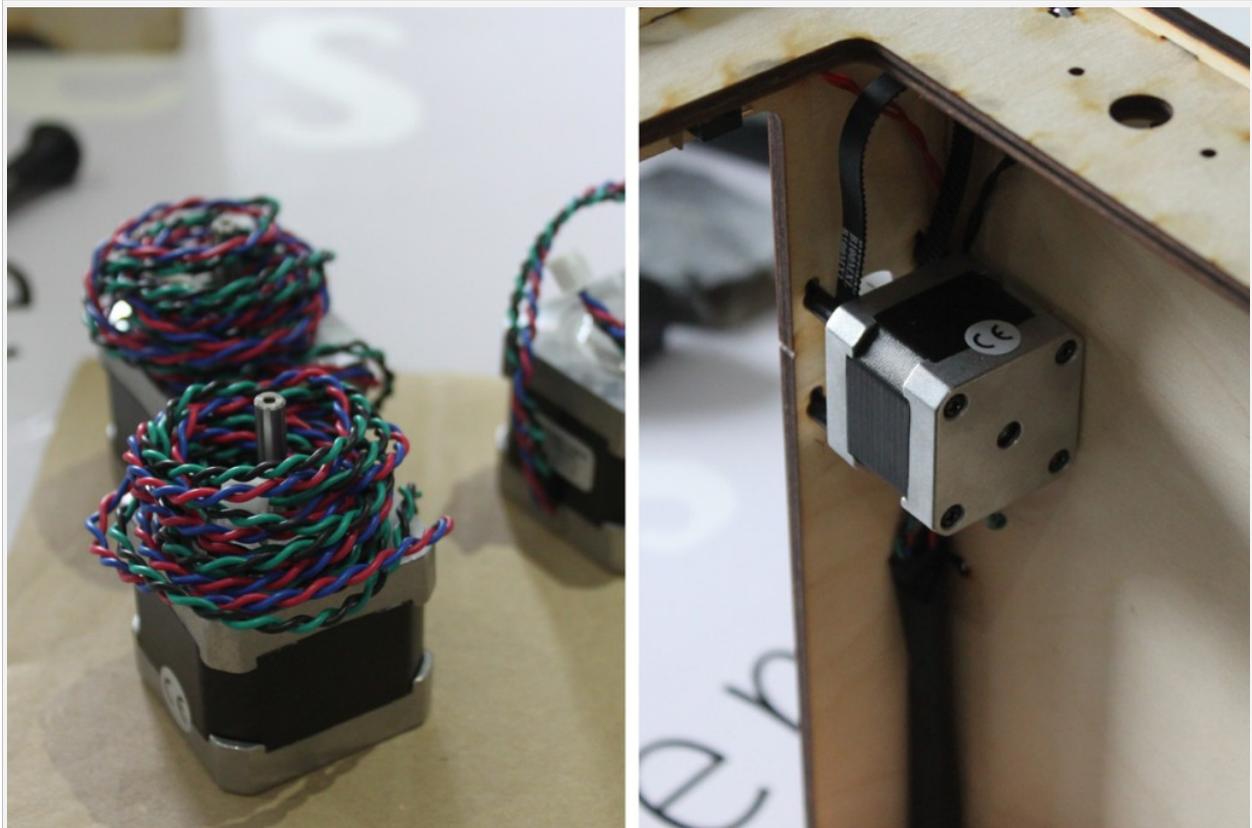


Illustration 4

Ultimaker Stepper Motors - Before and after installation

© 3Dprintingforbeginners.com

## Extruder

Contrary to what you might think, the word extruder does not necessarily refer to the part of your 3D printer that squirts out the molten plastic. The extruder is actually the part that is responsible for feeding the filament into the so-called "hot-end". Extruders are the part where some of the biggest differences between 3D printers exist and where we are still likely to see some of the biggest developments in the future. Some 3D printers models use extruders which integrate the "filament driver" as well as the hot-end in one single piece. **Illustration 1** already gave a brief overview of such an "integrated extruder". Better still probably is a close-up photo of a Printrbot Simple 3D printer, as shown in **Illustration 5**.

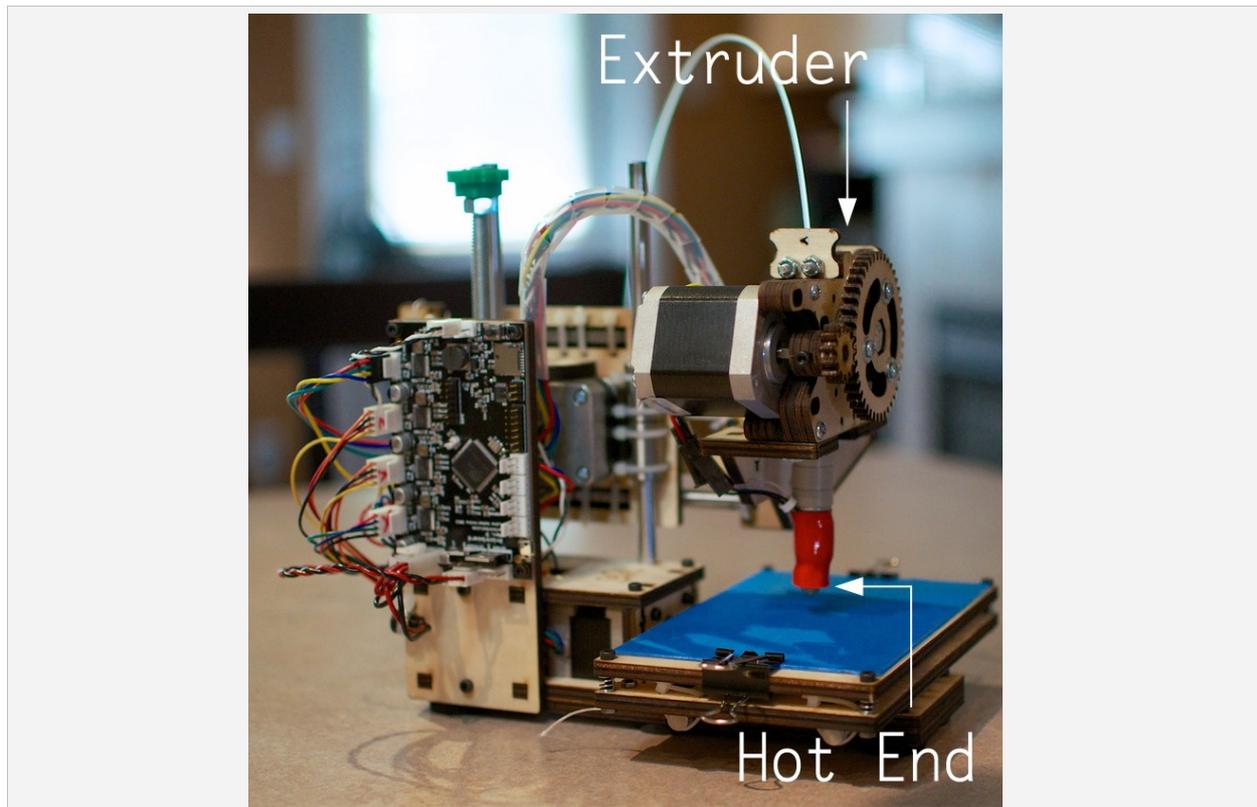


Illustration 5

Integrated extruder on a Printrbot Simple ©johnbiehler.com

Other printers, like our Ultimaker Original, have a "material feeder" or a "filament driver" (i.e. the extruder) separated from the "extrusion head" (i.e. the hot-end). Just have a look at **Illustration 6** for a better understanding of this particular setup.

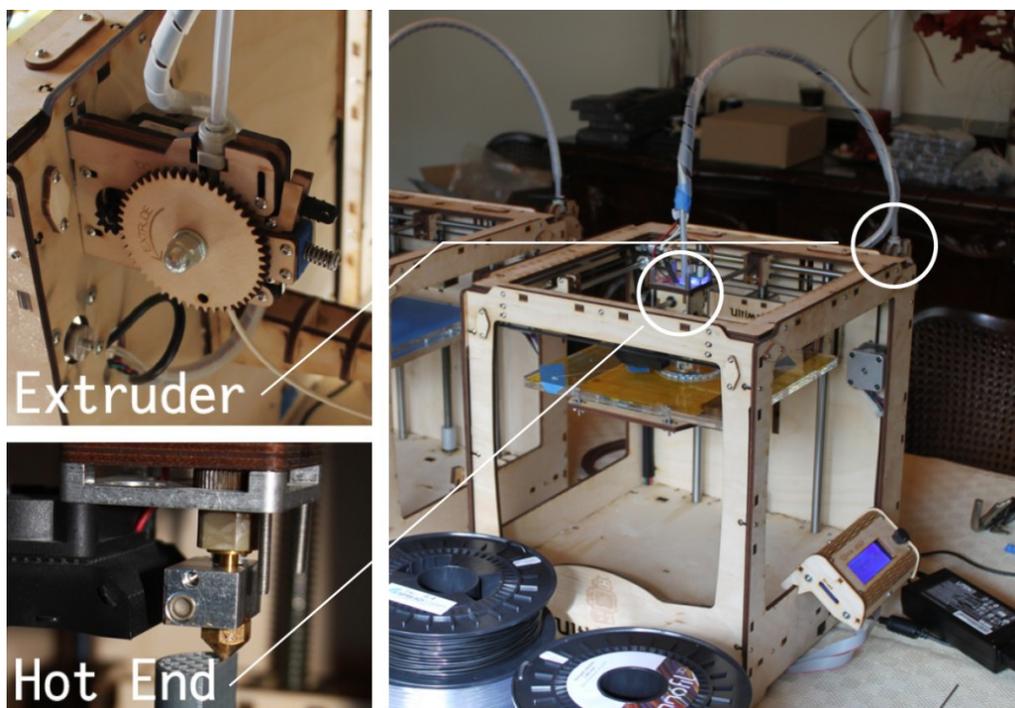


Illustration 6

Detailed views of the extruder and the separate hot-end and their respective positioning (circles) on the Ultimaker

The confusion around the wording used to describe 3D printer parts stems from the fact their exact terminology is not yet fixed. Especially if you consider that the action of pushing the heated plastic through a print nozzle is called extruding - pretty frustrating, isn't it?

Anyway, both systems, the integrated type extruders or the remote one's both have their pros and cons. Integrated type extruders don't need a complicated filament delivery system - just look at **Illustration 5**, where you can see the filament arrive directly into the extruder of the Printrbot Simple. These extruders therefore rarely exhibit feeding problems (like friction problems caused in Bowden-cable type systems - see below), but they are heavier than remote extruders. Due to added weight and bulkiness, the integrated type extruders generally are far slower than the remote extruders and this lack of speed results in longer print times. An advantage however is the ease with which one can change the filament - no hassle and no time loss.

The remote type extruder systems generally push the filament through a hollow cable (Teflon or a similar material) in order to obtain a permanent feed of thermoplastic material to the moving hot-end. This sort of setup is called a "Bowden cable", which are flexible cables used to transmit mechanical force by the movement of an inner cable (filament) relative to a hollow outer cable housing. The Bowden cable therefore does not only ensure the permanent feed of filament to the connected hot-end but also enables retraction of the filament if needed. Retraction is an important technique in 3D printing in order to obtain clean prints (read more on retraction below). In order to control filament feeding or retraction, a "filament driver" is connected to a stepper motor. The filament driver (normally a toothed/grooved bolt) and a push wheel at its opposite side squeeze the filament and via this torque and pinch system, they overcome friction and manage to push the filament through the Bowden-cable (cf. **Illustrations 7 and 8** for detailed views of "pinched" filament).

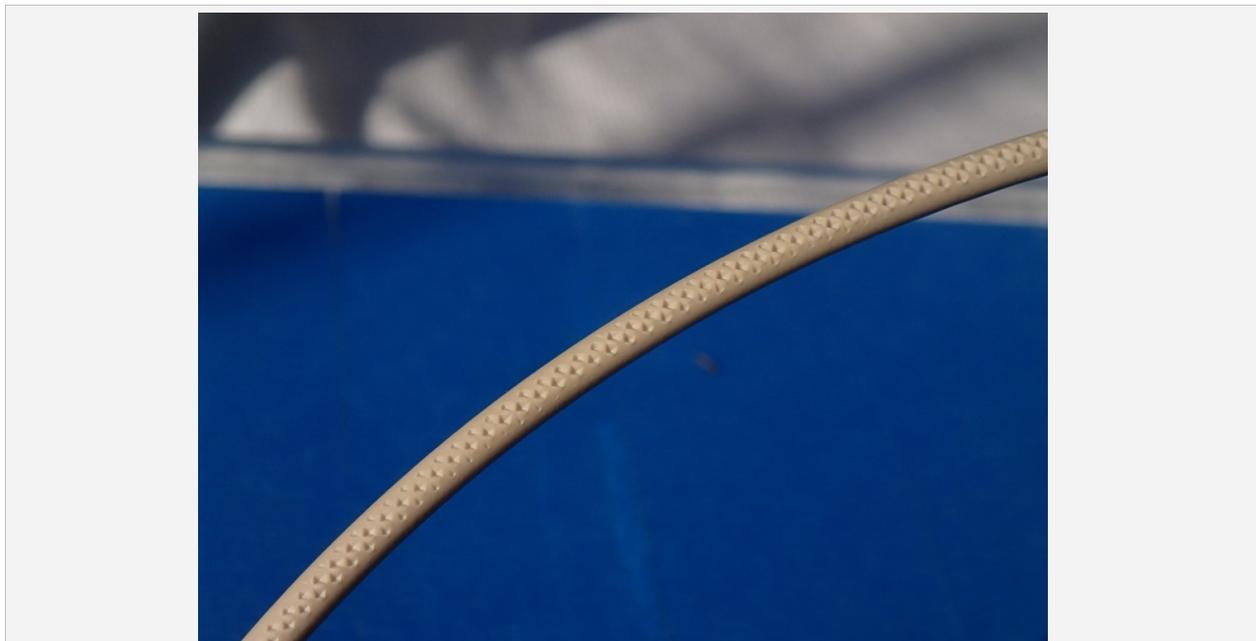


Illustration 7 - Grooved drive marks



Illustration 8 - Grooved drive marks

© 3Dprintingforbeginners.com

The problem is that the Bowden-cable setup does create a lot of friction and the extruder systems, especially the feeding systems on early printers were often having feeding problems. Also, certain materials like for instance flexible PLA do create quite a lot of friction, as their rubbery surface chafes while being pushed through the Bowden cable. Therefore, 3D printing enthusiasts are permanently looking for better solutions and, in true Maker spirit, created a lot of 3D printable alternatives for extruder systems. Just have a look at **Illustration 9**, picturing the incredible Rollerstruder, a complete replacement of the Ultimaker extruder developed by Jeremie François - available at: <http://www.thingiverse.com/thing:73082>.

The big advantage of the remote type extruder system however is that the hot-end is very lightweight, which results in quicker travel speeds as well as quicker prints. Our Ultimaker original does use a remote extruder and this explains why this printer is among the quickest 3D printers in its class.

Another slight disadvantage for such a Bowden-cable style setup is that changing the filament can sometimes be a bit of a hassle, as you need to work out what procedure works best with your specific printer. We always heat up the print head first, before trying to remove any kind of filament. This is necessary, as the filament cools down after printing (the printer by default is set to cool down after finishing a print). By cooling down, the filament gets stuck to the melted but not yet extruded plastic left

in the heating chamber. You should never try to yank it free with force. Simply heat it up and gently pull back on the filament reel, after opening your material feeder mechanism. Or make and install Jeremie's system, which also allows for a quick filament change.

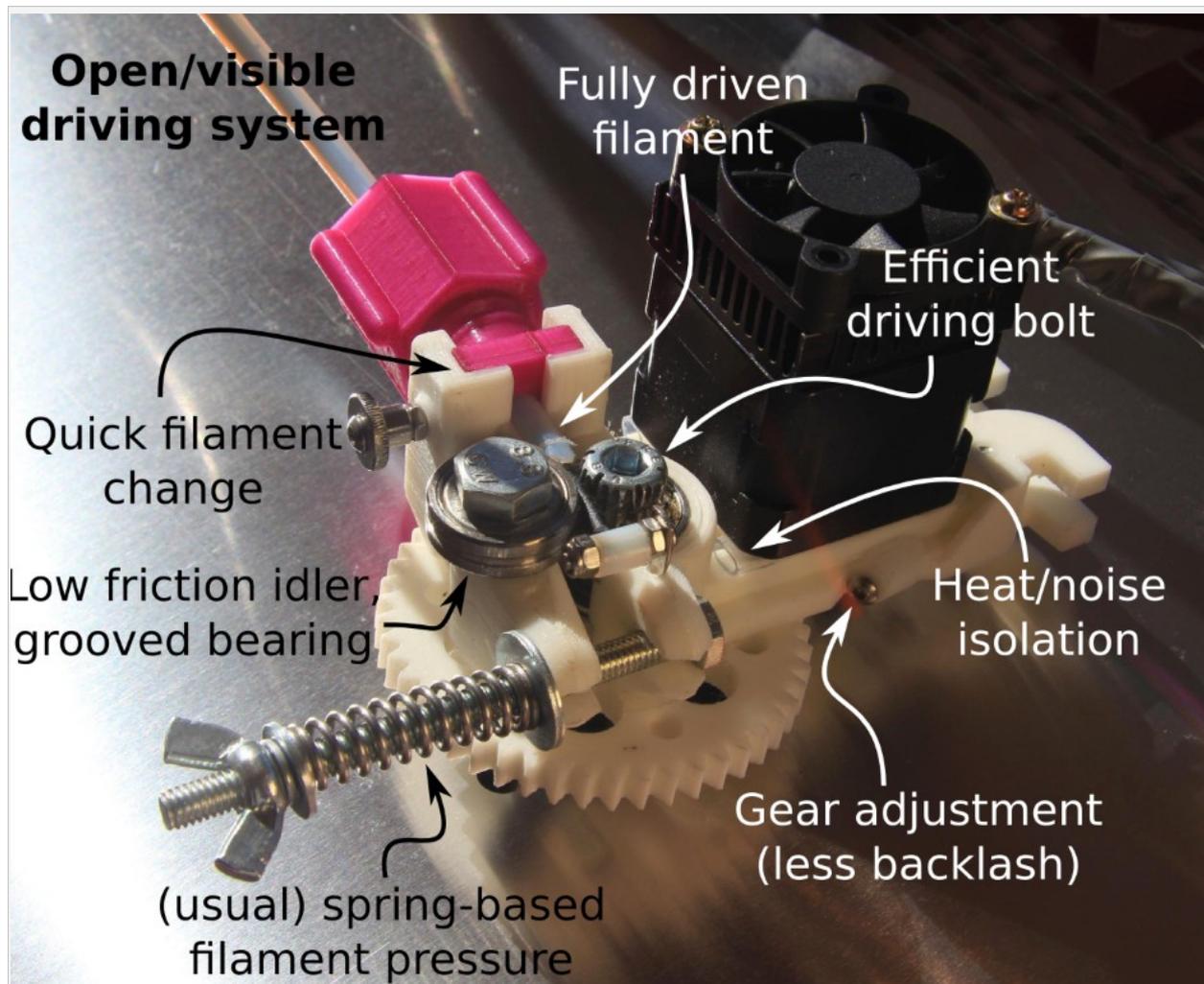


Illustration 9 - © Jeremie Francois

## Retraction

Retraction is a special technique used in 3D printing, whereby molten plastic is "sucked back" into the heated hot end, while printing. On an Ultimaker, you will notice that, while retracting, the "material feeder" drives the filament in the opposite direction than usual. It does basically pull a small part of filament back through the Bowden tube. The effect of this can be compared to squeezing the edges of your toothpaste tube to suck back in some of the excess toothpaste you accidentally squirted out.

While printing a part, molten plastic is normally extruded continuously, except when the nozzle needs to create a gap or jump across a gap to the opposing part of the wall or another part. As the extruded thermoplastics are not completely liquid, they tend to create cobweb-like thin strand of plastic which

tend to follow the nozzle across that gap. In order to obtain a proper print, you would need to clean those strands, which is messy and time-consuming. The solution is to retract the filament back up into the nozzle just before jumping across the gap or the new part. Then, upon arrival at the other side, the filament is pushed back to where it was before retraction. This effectively eliminates the "cobweb creation", which also known as "stringing".

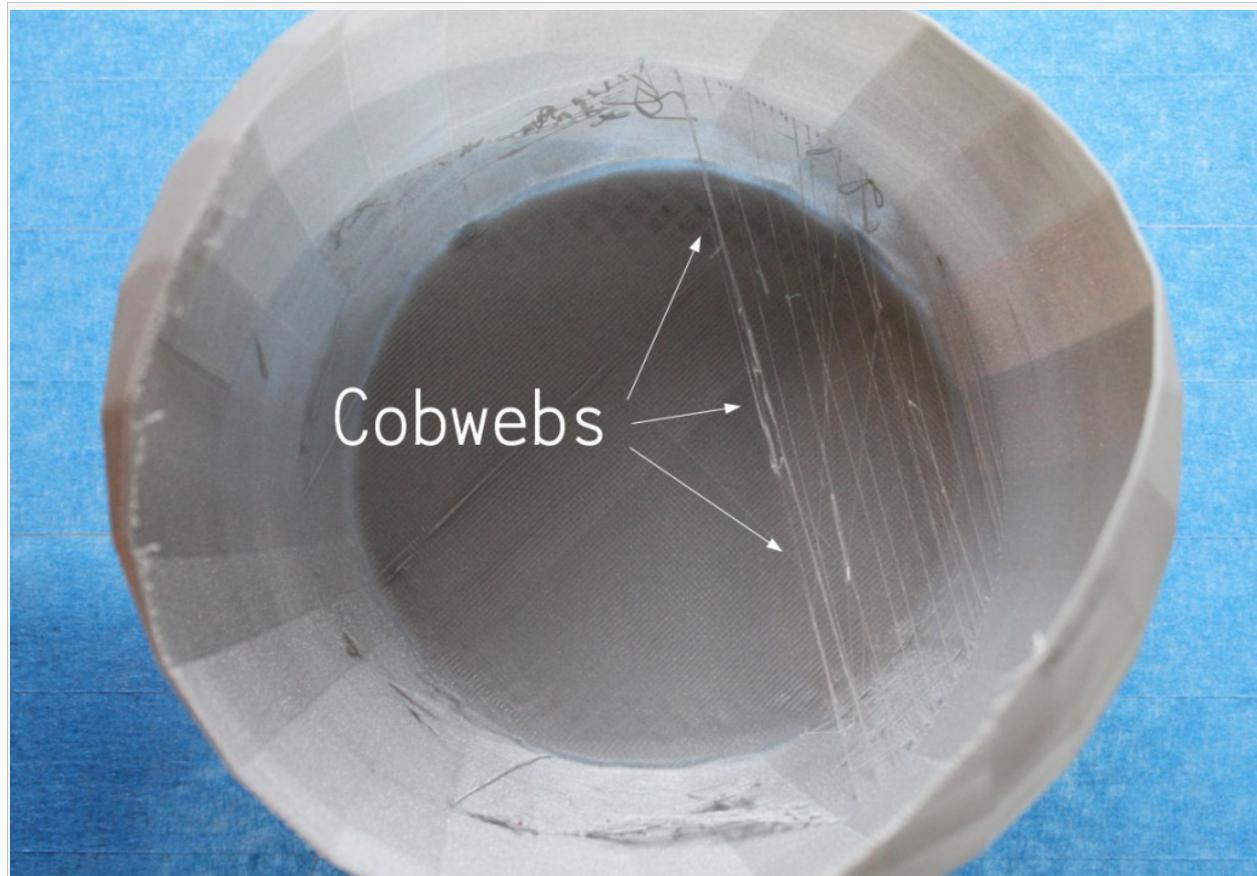


Illustration 10 - © 3Dprintingforbeginners.com

## Dual Extruder

Some FFF printers feature a dual extruder. This means that the printer has two filament drivers as well as two hot-ends. Check out **Illustrations 11 and 12** to get a better idea of what a dual extruder system looks like.



Illustration 11 - © Makergeeks.com



Illustration 12 - © Notcot.com



Illustration 13 - © Tested.com

The advantage of this particular feature is that you can feed two different filaments for one print, enabling you thereby to either print in dual colour (look at the great two-coloured cat in **Illustration 13**) or even with two different materials. Why two materials you ask? Well, as you know, 3D printers print from the ground up. But some prints are impossible to realise, as the printer cannot print on air; that's why you need "support structures" or support, in short. The parts of your print which would be floating on air are called "overhang". Check out **Illustration 14** to see the identified "overhangs" in the piece to be printed - the red circles.

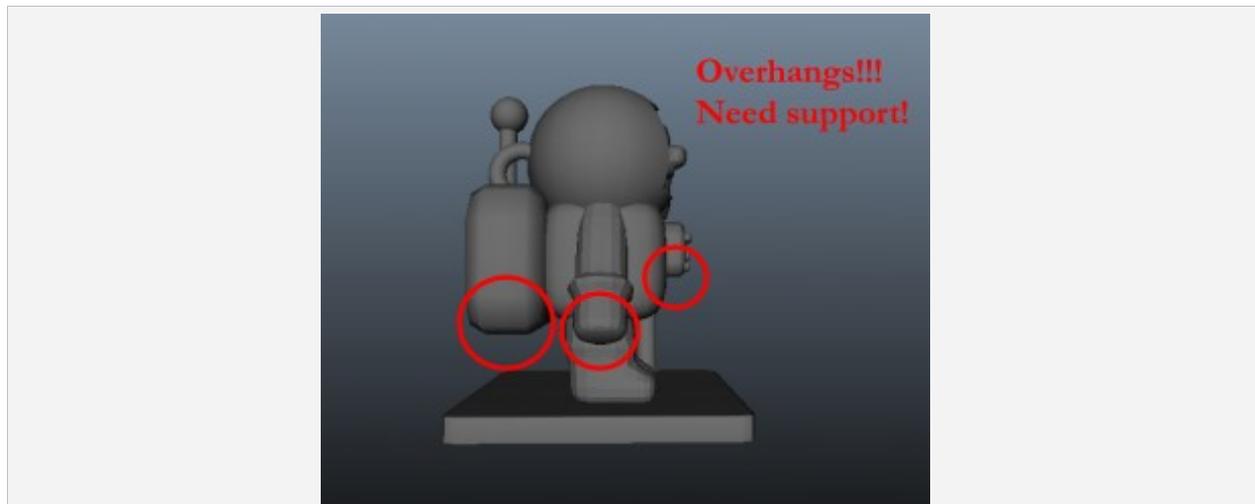


Illustration 14 - © Cubify.com

Basically, the limits of your print are the laws of physics. In order to overcome this problem, you can choose (or, depending on your software, these parts are automatically detected) where to print a support structure. Check out the 3D printed cat model below. You could never have printed this object with an FFF printer if you did not use a support structure.

**Illustration 15** shows you the printed product, with its support structure and **Illustration 16** shows you the finished cat, after cleaning the support structure away.

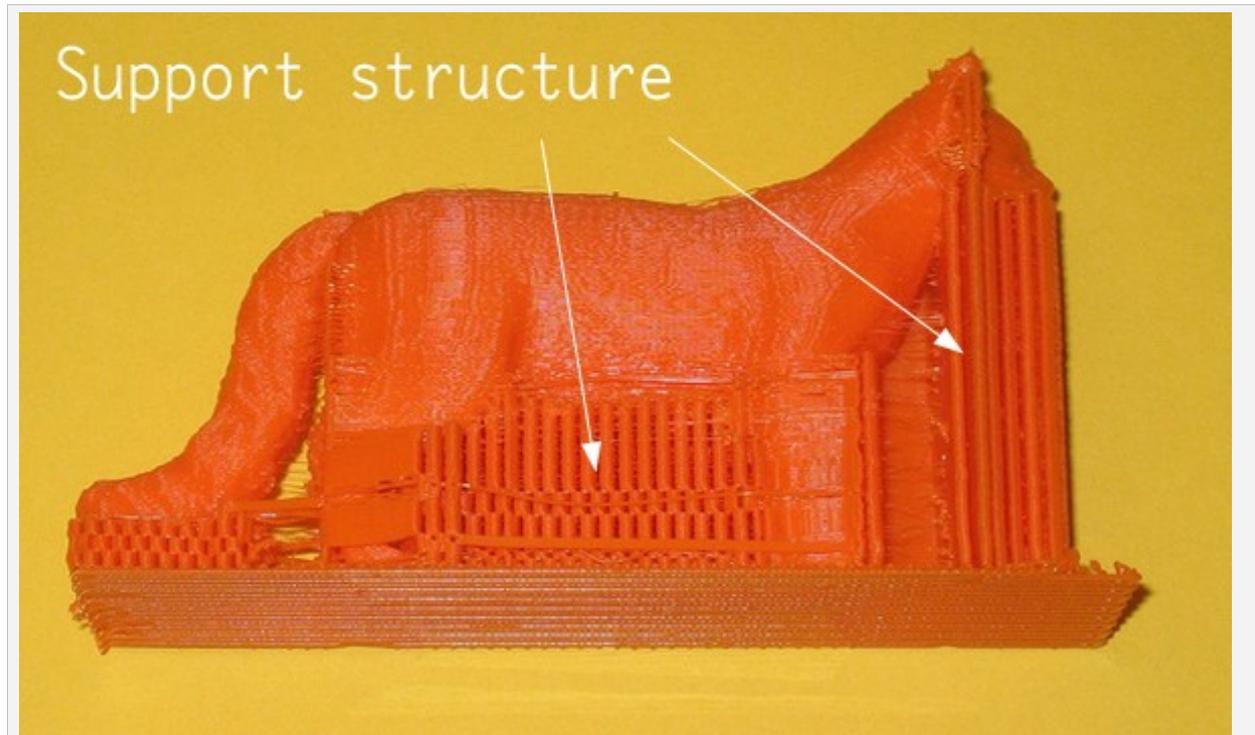


Illustration 15 - © John Baichtal, Makezine.com



Illustration 16 - © John Baichtal, Makezine.com

If you are printing with PLA or ABS, you need to know that the plastic will get pretty stiff after cooling down - so cleaning the support structure can take quite some time. Also, you need to pay attention not

to damage your print, especially if you use a knife or a power tool like a Dremel.

An easier way to get around this is printing with PVA on the second extruder. PVA, short for polyvinyl alcohol, is a special water-soluble thermoplastic. PLA is used to print your object and PVA is used to print only the support structure. Once your print is finished, just put it into water for some time and the PVA support structure will dissolve itself (check out our [materials post](#) to get more information on PVA). Voila, you have a perfect print without the hassle or time loss for cleaning up your object.

**Illustrations 17 to 19** demonstrate how this technique works. The same also works with printing ABS in conjunction with HIPS (High Impact Polystyrene). HIPS can be dissolved in Limonene, a chemical dissolvent widely available. The big advantage over PVA is that HIPS is far less hygroscopic, i.e. it does not attract water from the air as easily as PVA. PVA needs to be stored in an airtight box, ideally together with some desiccant (like silica gel), so that all the moisture in the air does not get absorbed by the PVA filament. HIPS is clearly the easier solution giving you less headache when it comes to storage.

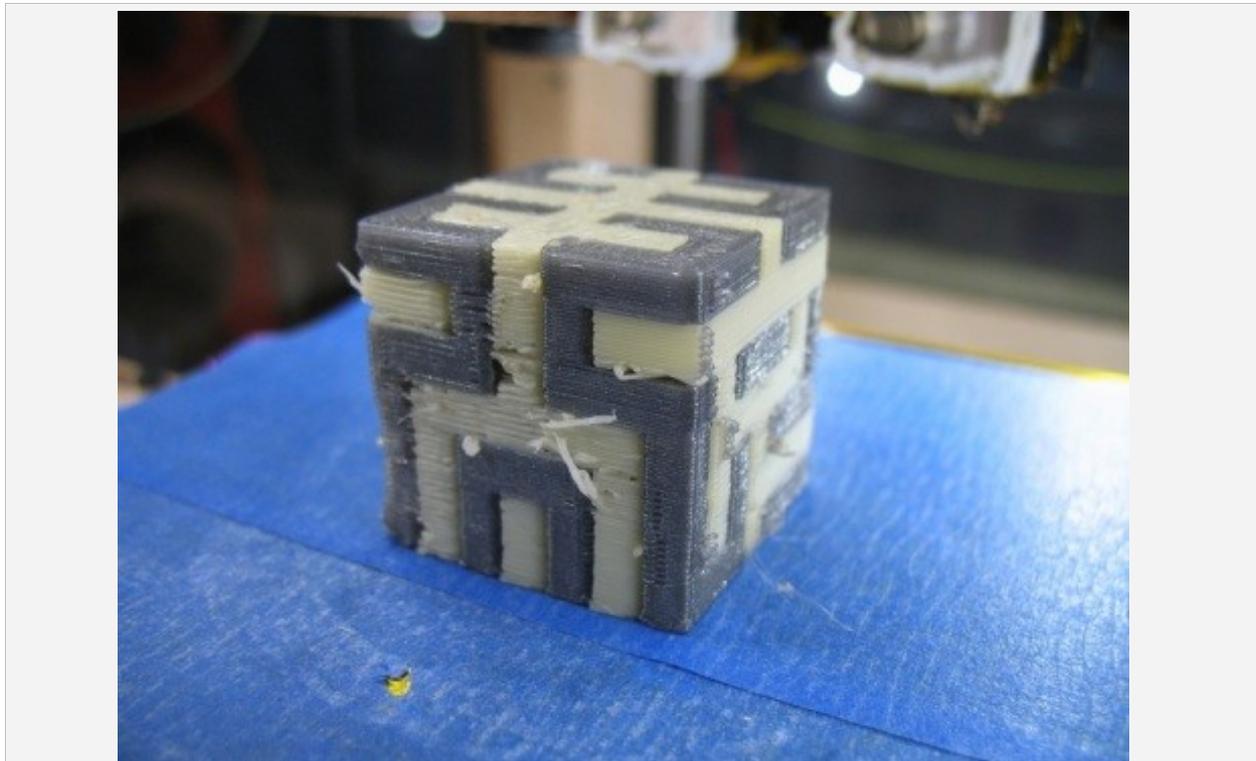


Illustration 17 ©Tony Buser

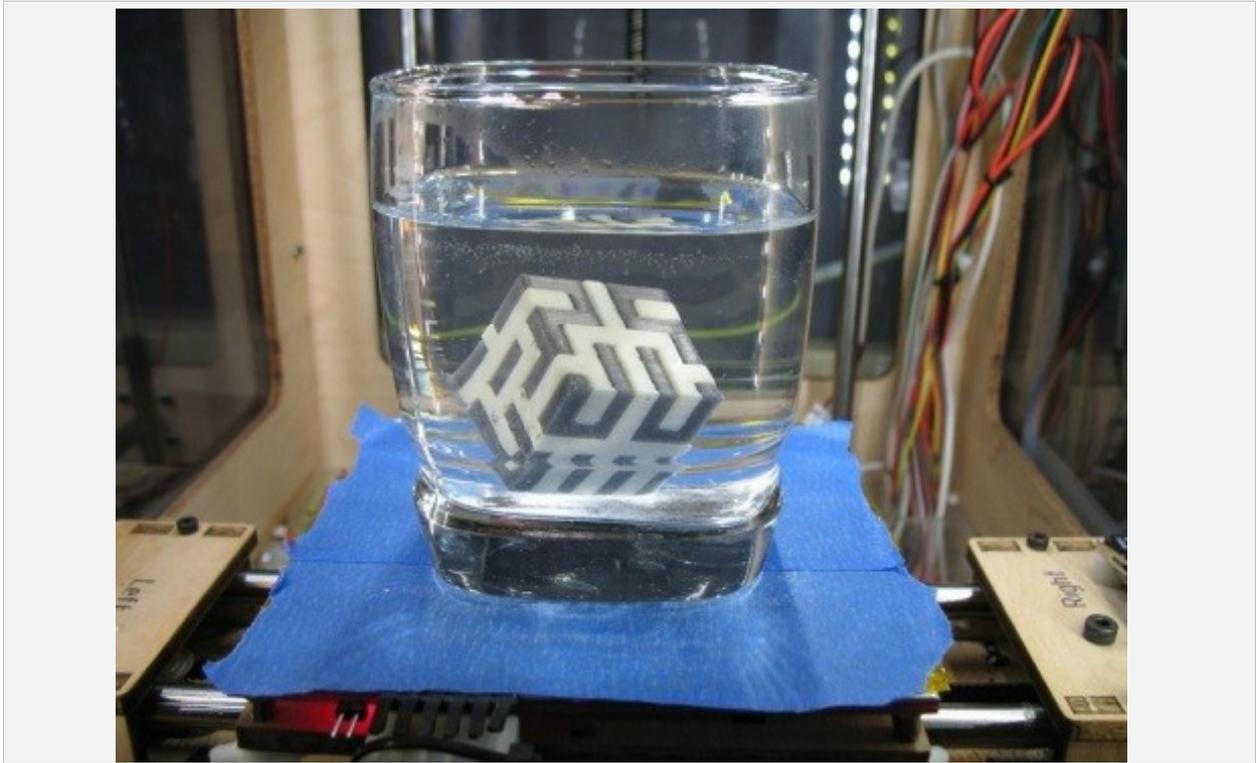


Illustration 18 ©Tony Buser

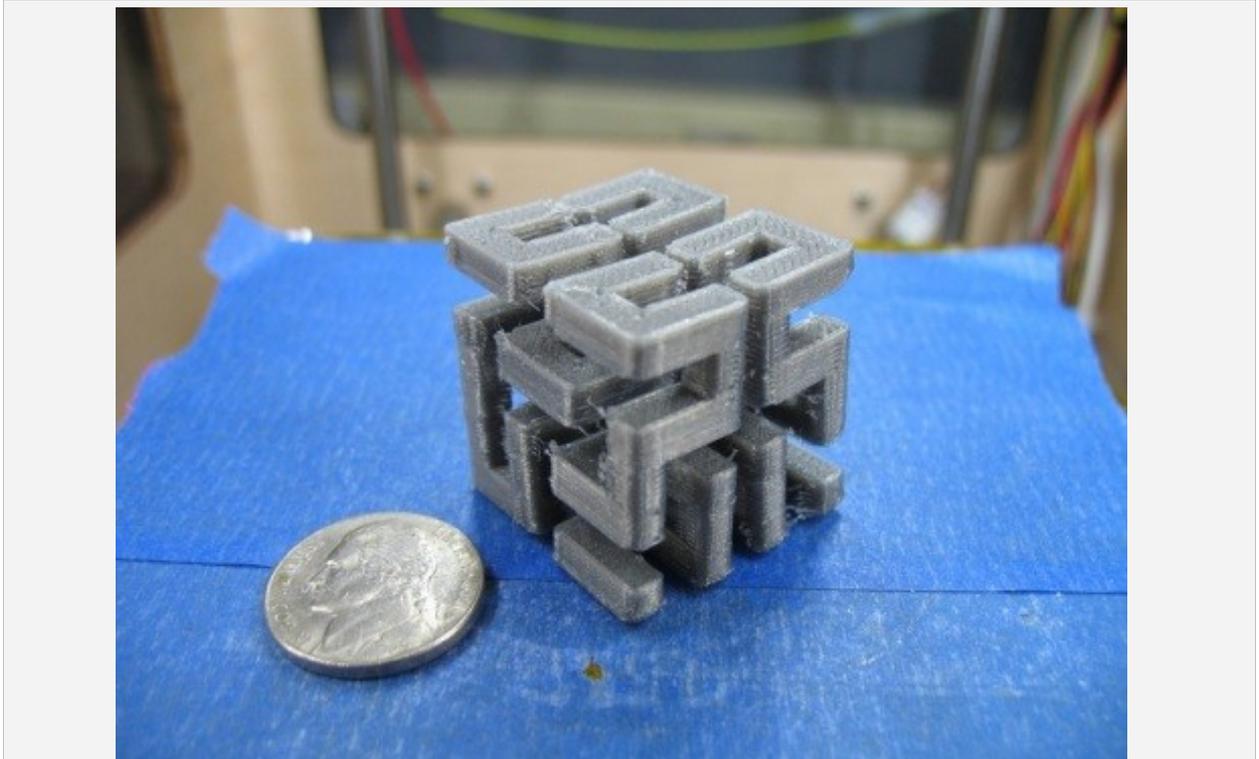
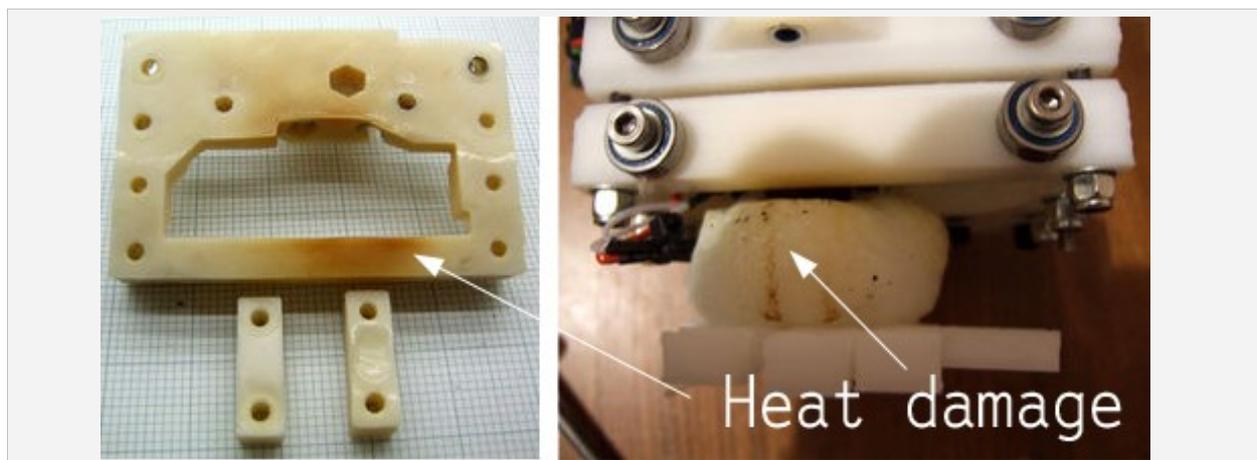


Illustration 19 ©Tony Buser

## Hot End

The hot end is usually made up of a bloc of aluminium (squared or barrel-shaped), which is heated up to temperatures up to 250° Celsius (482° Fahrenheit). These high temperatures are the reason why the hot end needs to be thermally insulated from the rest of the setup - you don't want other parts of your expensive printer to be roasted or otherwise smoulder away.

Excessive heat damage is shown in **Illustrations 20 and 21**, although 3D printers are generally considered quite safe, as only very few cases where a printer caught fire are known. The hot end is also comprised of a print nozzle (a.k.a. extrusion end) and some sort of temperature sensor. The typical print nozzle's opening diameter may range in size between 0,2 to 0,5 millimetres and plays an important role in the print resolution of your object. The smaller the nozzle, the finer the print, but the longer it will take to complete. The presence of the temperature sensor is important, as different sort of plastics may need different temperatures to print with.



Illustrations 20 & 21 - Heat damage examples - © Reprap.org

Functionwise, just imagine the extruder feeding/pushing a steady part of filament (normally bundled on spools) towards the hot end. The filament will go into the heat chamber/heated bloc, become semi-liquid or even liquid because of the heat and will then be pushed towards the nozzle. As the print head moves to the according XYZ position, the molten plastic is squeezed out of the nozzle and deposited in very fine strands on the printbed. The plastic nearly immediately hardens after being squeezed through the print nozzle (fans may help the cooling process of the thermoplastic). The repeated action of this results in putting layer upon layer in order to create an object in 3 dimensions. Please refer to **Illustration 1** to see a very simplified schematic of this process.

## Printbed

The printbed is the surface upon which the printed part sits on while being built. The most common printbeds are made out of Plexiglass (acrylic), aluminium or glass. We have even created one out of carbon fiber; we will publish a detailed article on this build soon. When buying a 3D printer, you should always check out what the exact printbed size is, as it plays a determining factor in the maximum size of your future printed objects. Also, you need to differentiate between simple (non-heated) printbeds and heated printbeds.

Non-heated printbeds normally need to be covered in blue tape (painters tape) or even Kapton tape (i.e. polyimide tape - very heat resistant) in order to make the print stick to the printbed. The tape helps with initial adhesion of the thermoplastic and keeps everything in place during the print. The object needs to be firmly fixed to the printbed, as the slightest movement of the printed object itself will most probably result in a botched-up print. As the adhesion factor of the blue tape wears out quickly, it needs to be replaced regularly. Instead of blue tape, some people recommend using glue, hair spray, sanding down the Kapton tape, etc. The biggest disadvantage of using a non-heated printbed is that you may experience warping (**Illustrations 22-24**) or cracking (**Illustrations 25 and 26**) of your prints. This is a direct consequence of the plastic cooling down too fast and the effects are especially prominent when using ABS plastics.



Illustration 22 © Reprap.org

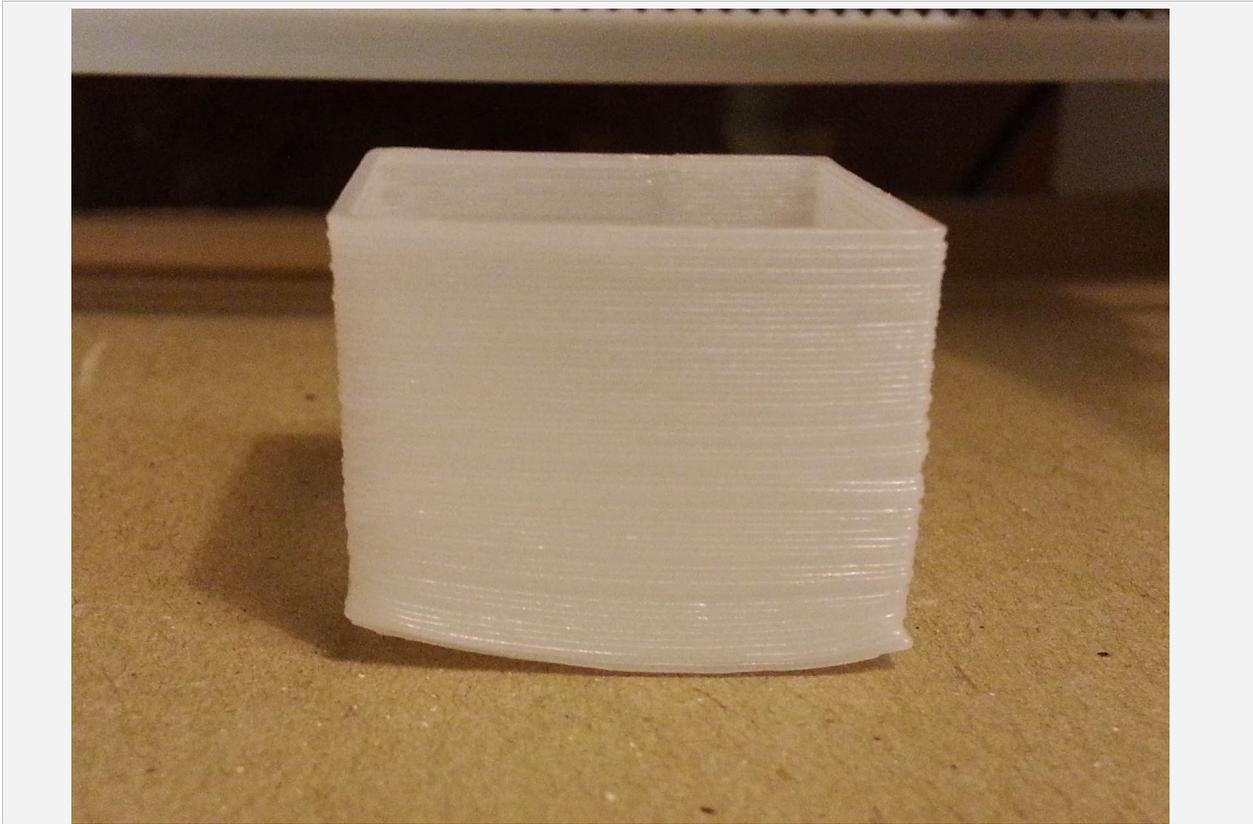


Illustration 23 © microfabricator.com

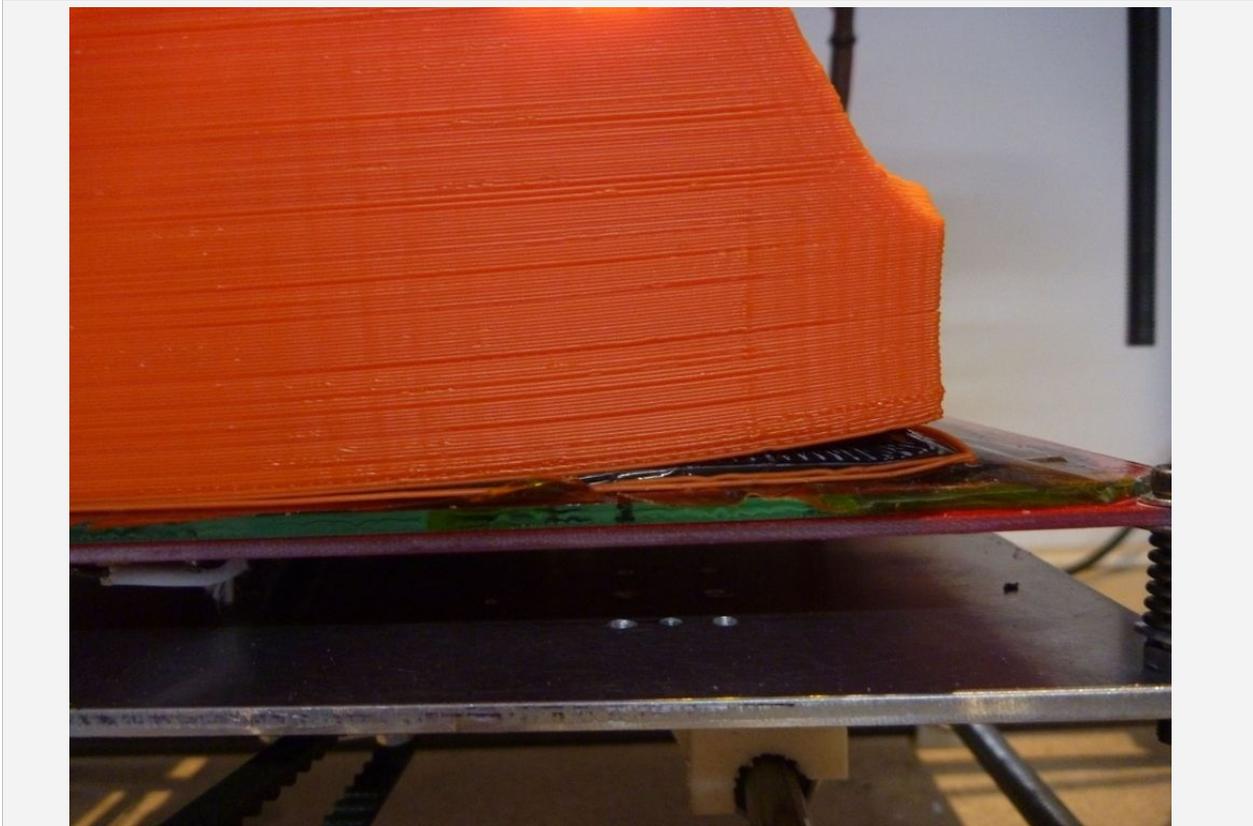


Illustration 24 © 3dprintedsculpture.com

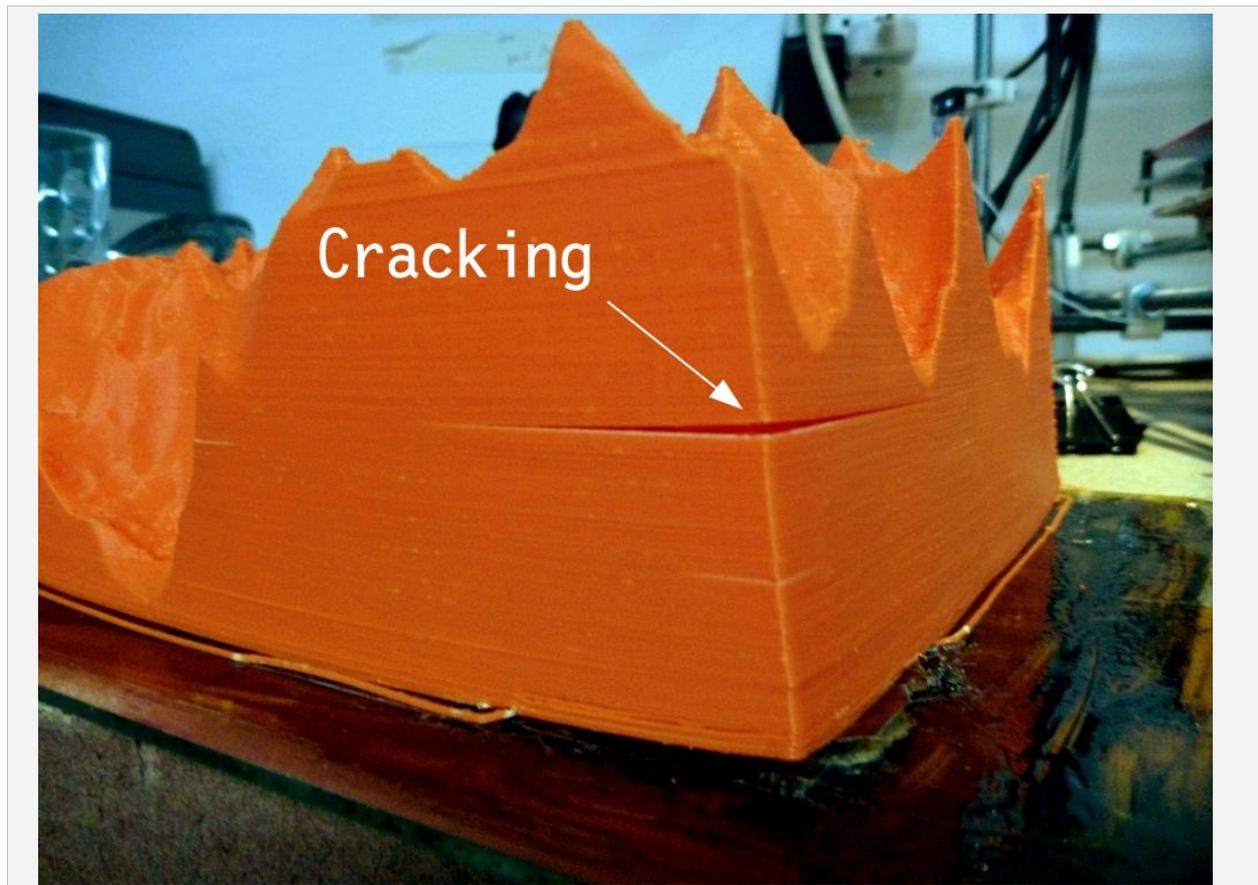


Illustration 25 © 3dprintedsculpture.com

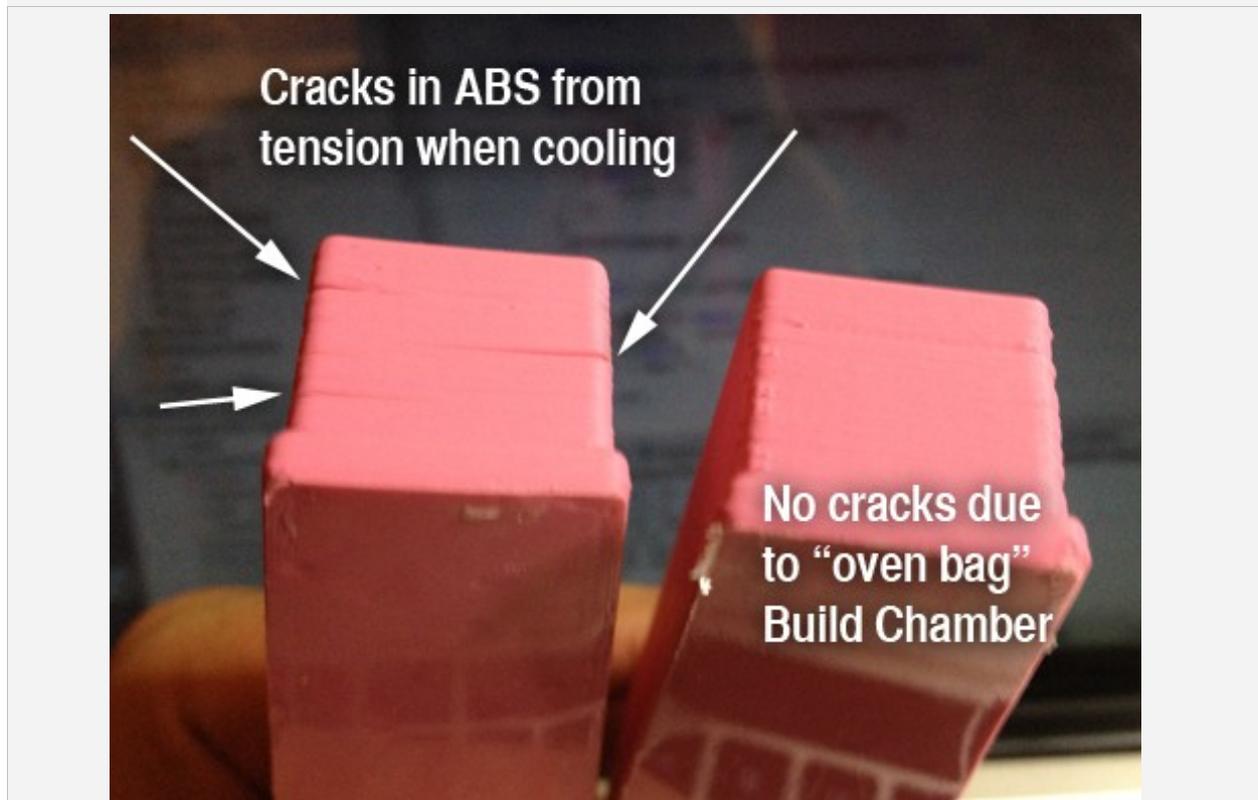


Illustration 26 © flashgamer.com

So if you don't want to build a heat chamber around your printer (check out **Illustrations 27 and 28**), you should consider buying a model with a heated printbed, or, in true maker spirit, build one on your own.



Illustration 27

Simple DIY Heat Chamber - © flashgamer.com

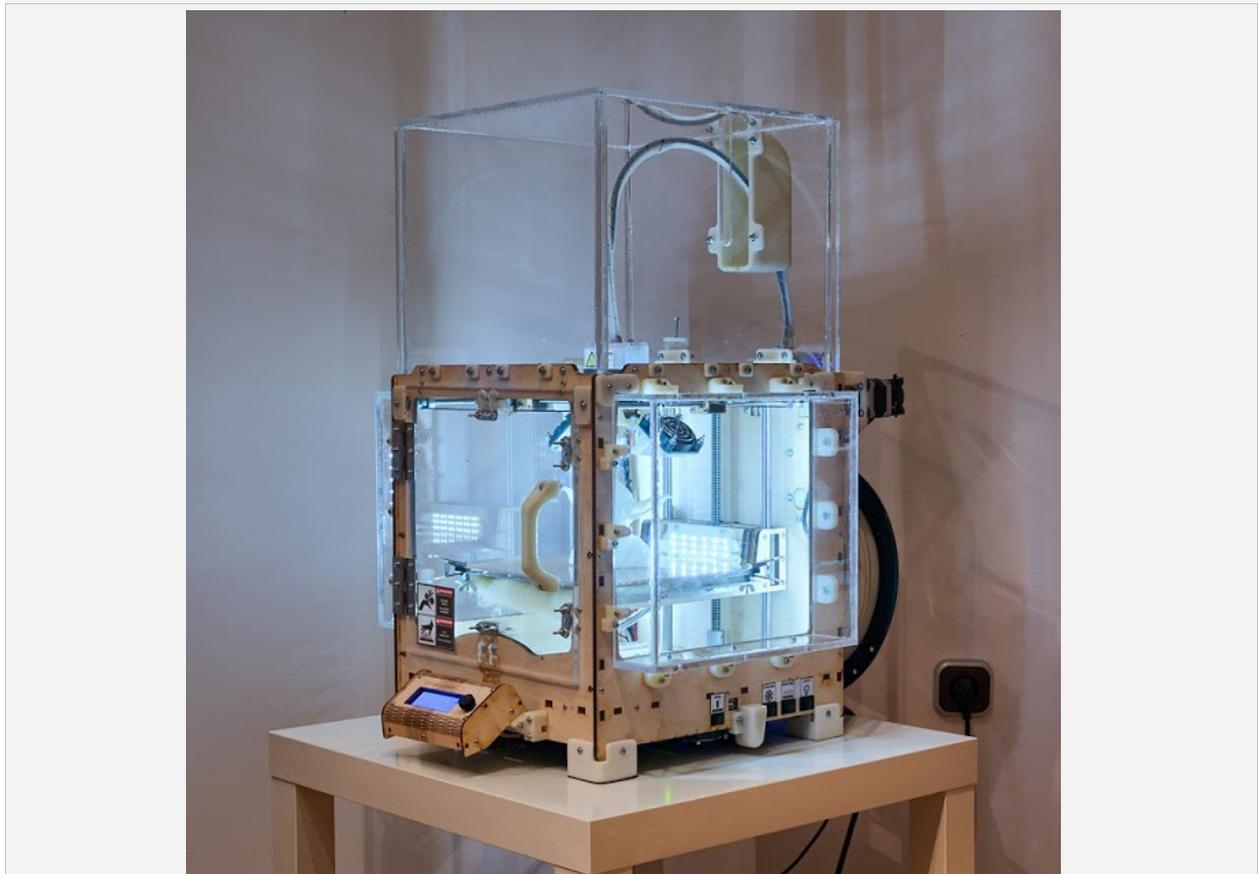


Illustration 28

Very elaborate DIY Heat Chamber - © diy3dprinting.blogspot.com

The heated printbed prevents warping of the prints while cooling down, but also provides for a much smoother surface of the first layers of the print. Normally, printbed temperatures vary between 60° to 110°C Celsius. The temperature is normally obtained via a printed circuit board, which is heated up using electricity.

But you should pay attention not to overdo it with heating up the printbed during the full print. If for example your print starts to warp at height, that is a telltale sign that you are heating too much - try a lower temperature setting on your printbed or reduce print speed. Also, too much heat may result in the print losing adhesion and/or start warping. Using the heated printbed with specific control of its temperatures will enable you to print ABS (and other materials prone to warping) without having to tackle the crux of it warping.

Not having a heated printbed on the Ultimaker original is possibly the only bigger drawback we could identify. We absolutely love working with it, it's quick, its build volume is great and you can obtain incredible detailed prints, but printing ABS is not easy, because of warping issues. The people at Ultimaker have identified this major issue and the new Ultimaker v2 is sold only with a heated printbed. Although we could not find any ready-made kits out there, it is not too difficult to source parts and find instructions to build a heated printbed on your own. We have decided to try this out and will post a detailed article on this shortly.

## Filament

Filament is the consumable for your 3D printer. Just as the inkjet printers we referred to earlier needed ink cartridges to work, a 3D printer needs filament in order to be able to print. Filament is usually bundled in spools (**Illustrations 29 and 30**), but some is also sold by the meter (ideal for test prints). Before making any purchase of filament, you need to know what filament diameter your printer works with. It will be either 1,75mm or 3mm, which are the two standard sizes.

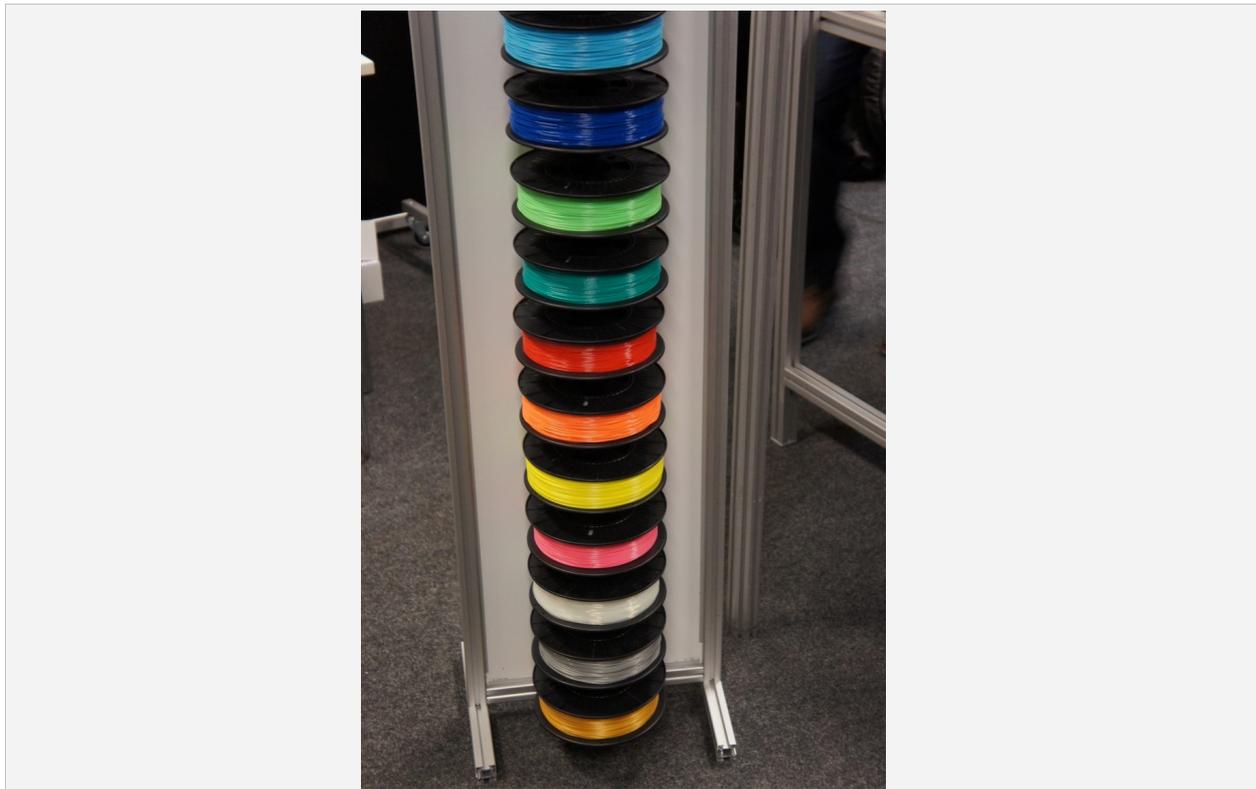


Illustration 29 - © 3dprintingforbeginners.com



Illustration 30 © iGo3D.com

There also exist many different filaments materials, but the two most common are PLA and ABS. Each material has its own physical and chemical properties, which means that each filament type needs its own specific setup within your printing software. While some materials can be extruded at temperatures around 180°C, others need to be heated up to 250°C or more, before being ready for printing. Beginners especially need to pay attention to the fact that a specific printer may not be able to print with a certain type of material. If in doubt, check your user manual or read up in forums specific to your printer model.

We also recommend that you read our [filament primer article](#), where we analyse different types of plastic like PLA, ABS and PVA as well as colour options in more detail. A big materials article is currently in the making, in which we will analyse the more "exotic" materials one can use to print. We will publish a big comparison table within this article, which may help any beginner with the settings for specific materials.

Also, always consider the specific use you are going to make of your filament. If, for example, the filament will be used for printing cups, kitchenware or body-worn jewellery, only do buy food-safe/body-safe filament. Some more recent filament types have not only reached officially recognized common standards, but they have obtained certified food-safe labels from official sources. Moreover, some filament are even certified dishwasher safe, which may be important, depending on your usage you want to do with your prints. Under no circumstance should the price be the only buying criterion when it comes to 3D printer filament!

Installing and using the filament is easy. Most printers have a kind of integrated filament spool holder on which to install the filament you want to print with. If you have no double extruder, the colour of your filament will also be the colour of your print. Filament is available in a very wide array of colours, so that you can bring colour into your prints and into your life.

*There you have it, 3D printing technology explained. We hope this article has helped in shedding some light on the topic and that you feel comfortable with the basic concepts of FFF now. Should anything still be unclear or if this article has raised new questions to your mind, feel free to post them in the comments section. We'll do our best to answer them!*