Introduction to 3D Printing for Hams

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3D Printing

In 1947 when Walter Brattain and William Shockley invented the first transistor at Bell Labs, a revolution began. In few short years, vacuum tubes and point-to-point wiring disappeared and the age of the computer had begun. 3D printing, though still a newcomer, has all the earmarks of becoming, as some are calling it, the third industrial revolution. In scarcely three decades it is already widespread worldwide both in industry and for DIY hobbyists, including hams. Anyone can buy a 3D printer today, begin printing useful and attractive items, and even become a manufacturer. 3D printing has indeed arrived.

Printing complex three-dimensional (3D) objects, as opposed to traditional fabrication methods, is new both to industry and to ham radio. Industry was the first to welcome it for prototyping but increasingly it is being used for volume production. Today's consumers, scientists, researchers, and hobbyists can design and fabricate plastic items as single custom units or in small quantities.3D printed objects are increasingly being seen in ham radio construction articles.

Because the technology is developing rapidly, today's best 3D printing choices won't be tomorrow's choices. Well-liked and most-used printers, software, information resources, printing materials, and methods of today will all evolve quickly. This shouldn't be a deterrent because exciting and practical uses for 3D printing exist right now. For the ham home builder, 3D printing is a technology that has arrived.

1. EARLY STEPS

The earliest 3D printing patents date back only three decades. This partly accounts for why new printers, new materials, and new 3D printing methods continue to appear frequently. Will the printer purchased today and the printing skills learned today remain valid? Fortunately, yes. The fundamentals of 3D printing can be learned by using common design tools with a representative printer. Detailed instructions on how to do 3D printing are not the intent of this article: 3D printing is too broad a topic. The internet abounds with videos and tutorials on every aspect of 3D printing. The object here is to provide the startup knowledge needed to open the door for the newcomer to a new set of tools and techniques.

Without a 3D printer, how does one begin 3D printing? Here are three possibilities. (1) There are likely to be ham radio club members who own a 3D printer and who might make a print. (2) There may be a nearby "maker space" or a local college that has 3D printers to use. Local colleges also offer 3D printing classes and have printers. And (3) there are many websites that will print from an uploaded design and ship the result.

One can begin by designing an object with 3D design software. An easier starting method might be to download a design's model file, often provided by the author of a *QST* or another magazine article, and have a friend print it or take it to a local maker space. 3D printing does not need to remain "undiscovered country" to the ham who wants to keep abreast of current methods.

2. WHAT IS 3D PRINTING?

Fabricating one-piece physical objects has traditionally been a *subtractive* process. That is, the builder starts with a solid volume of material, and like a sculptor, gradually removes or subtracts material until it is in the final form. Lathes and mills are typical of the tools used to remove material. An *additive* process, however, builds the object by depositing or printing a sequence of layers of material, usually as 2D layers called *slices*, each adhering to the previous layer, until the entire 3D object has been constructed. Each method has its advantages but 3D printing technology has brought sophisticated modeling and manufacturing in reach of the home hobbyist.

For the home hobbyist, the most widely used method is *Fused Deposition Modeling* (FDM), also known as *Fused Filament Fabrication* (*FFF*). It is affordable, easy to learn, and offers high print quality. Its popularity is due to the large number of 3D printers available.

An FDM 3D printer creates an object by depositing fine strings of plastic in layers. The strings are created by heating the plastic until it is soft enough to be forced out of or *extruded* from a nozzle. The softened plastic immediately sticks (*fuses*) to the previously deposited layers below. The general process of building an object in layers is called *additive molding*.

FDM is the dominant method most often seen in ham magazine construction articles featuring 3D printed objects. FDM was patented in the 1990s by the 3D printing giant Stratasys. By 2007, Stratasys held 44% of all 3D printing patents. Licensing costs to printer manufacturers were high and home 3D printers were rare. In 2009 the Stratasys patents expired and MakerBot (now owned by Stratasys) and others began offering domestic 3D printers for the mass market. Prices plummeted and the public expected to see 3D printers in the home, turning out everything from car parts to children's toys. However, the public does not generally have the software skills to design 3D objects to print. Enterprising DIY hobbyists and small business owners do. Hams who enjoy home brew projects are very capable of learning 3D design and that is the intended audience for this article.

For reference, here is a short list of other 3D printing methods. Several are used primarily in industry today but two are now common in the home shop, SLA and SLS.

- SLA — Stereolithography
- SLS — Selective Laser Sintering
- 3DP – Tridimensional Inkjet Printing
- PJP — Polyjet Printing
- LOM — Laminated Object Manufacturing
- DLP — Digital Light Processing

SLA uses an ultraviolet laser to cure and solidify liquid resin one layer at a time. SLS, still in development at the hobbyist level, uses powdered nylon distributed by a blade and fused (melted together) with high-power laser pulses. Both are more expensive and have fewer printers available than FDM.

3. UNDERSTANDING THE FDM 3D PRINTER

3.1 The Extruder

Figure 1 is an example of a common home 3D printer extruder. Plastic filament (commonly 1.75 mm in diameter) is pushed into the top (cold end) of the extruder by knurled rollers at a controlled rate. At the bottom (hot end), a temperature-controlled heating block softens the filament to make it sticky. Then, under pressure from more incoming filament, the soft plastic extrudes through a tiny hole in the extruder's nozzle to fuse to the 3D object forming on the *build plate* below.

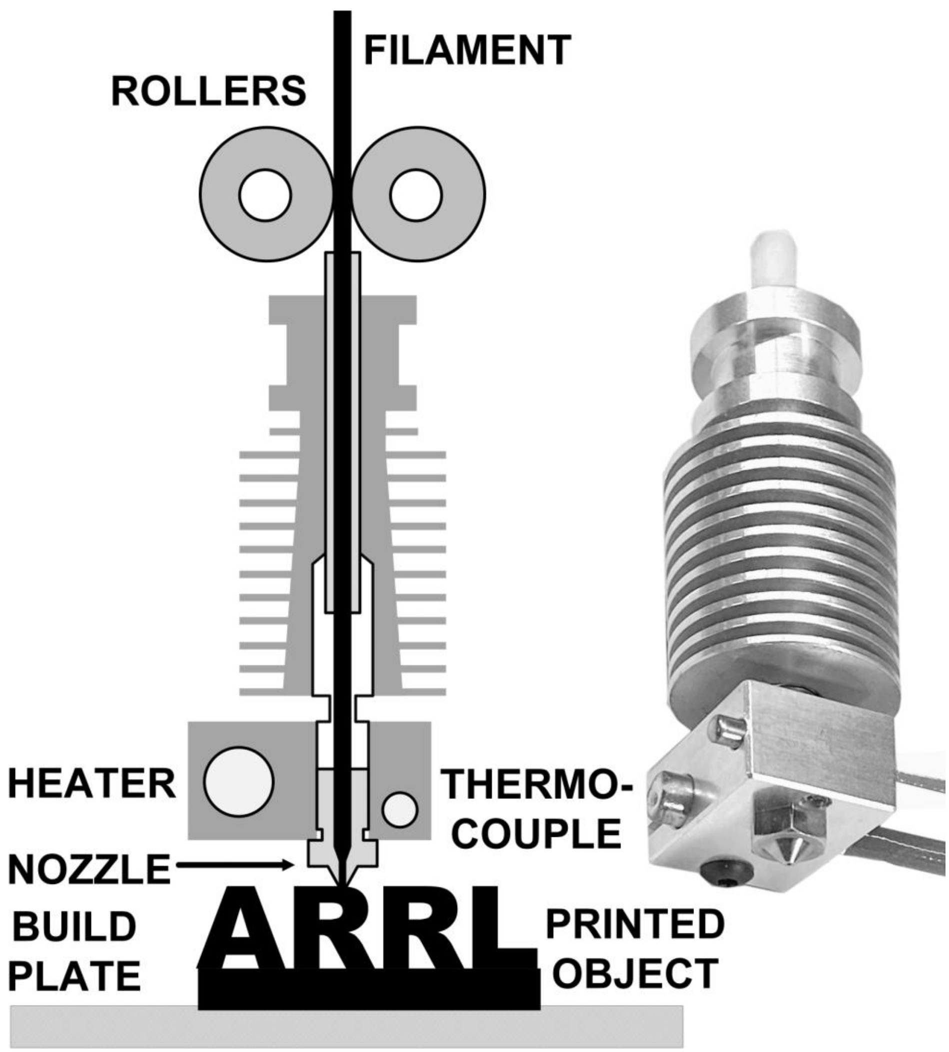

Figure 1— An FDM extruder

A typical extruder nozzle diameter is 0.4 mm, slightly less than 1/64 in. Nozzle diameter and the material from which the nozzle is made can be changed to suit the type of plastic and the detail of the print. Fineness of the extruded string is also affected by the speed with which the bead is extruded.

3.2 The Build Plate

The build plate is not just a passive metal surface. There are a number of important factors for the build plate. The surface must be flat and adjusted to be level with respect to the motion of the extruder. Most build plates have an aluminum base but the extruded plastic is not deposited directly on the base. Various surfaces are added, such as a flat glass plate, a self-adhesive plastic film or one or two types of tape. Further, an adhesive is commonly applied to make sure the first layer stays in place. A well-adhered first layer is a critical factor in obtaining a high-quality print and in avoiding *failed* or *mis-prints* in which the object is distorted, extruded plastic fails to fuse properly, etc.

The build plate on many FDM printers is heated to facilitate adhesion of the first layer and also to reduce warping of the object during the print. It also increases the variety of different plastics that can be used and reduces the number of failed prints. Selecting the right material and adhesive for the build plate are covered in more detail later in this article.

3.3 Computer Numeric Control (CNC)

The motions of the 3D printer's extruder and values of other parameters, such as temperature and extrusion rates, are controlled by a micro-computer from a programmed sequence of positions and values in numeric form. This physical/electronic architecture is *Computer Numeric Control* (*CNC*). Numerically controlled manufacturing began as programmable looms in England's early eighteenth-century textile industry and played a significant part in the industrial revolution. CNC machines today include milling machines, X-Y drafting plotters, laser cutters, and 3D printers. Some exceptionally large industrial 3D printers print with materials other than plastic — metal and even concrete.

Just as fundamental to 3D printing as the extruder are a printer's movements. To be able to print in three dimensions (X, Y and Z) the printer must be able to rapidly move the extruder from side to side (X), front to back (Y) and up and down (Z). The extruder typically moves only in the X and Z dimensions; the build plate moves in the Y direction.

A familiar home example of a CNC machine is an ink-jet printer. It is a CNC machine, just one that moves a print head and a sheet of paper in only two dimensions, X and Y, as it deposits spots of colored ink onto the paper. Its basic architecture, however, is very much the same as a 3D printer extruding hot plastic onto a build plate.

A 3D printer's X, Y, and Z motion is generally produced by *stepper motors*. Stepper motors or just "steppers" are a specialized type of motor designed to move in tiny precise increments. Most 3D printers use three steppers to provide the X, Y and Z motions. A fourth stepper feeds the plastic filament into the extruder at a computer-controlled rate. Other mechanical/electronic architectures are possible but this is the most common.

Figure 2 shows the X, Y, Z (and filament) stepper motors in a popular 3D home printer, a Prusa i3 MK3s. Most 3D printers use this architecture. Notched or toothed belts, pulleys, and threaded lead screws transfer the controlled rotations of the stepper motors to the build plate, the extruder, and the rollers feeding filament into the extruder.

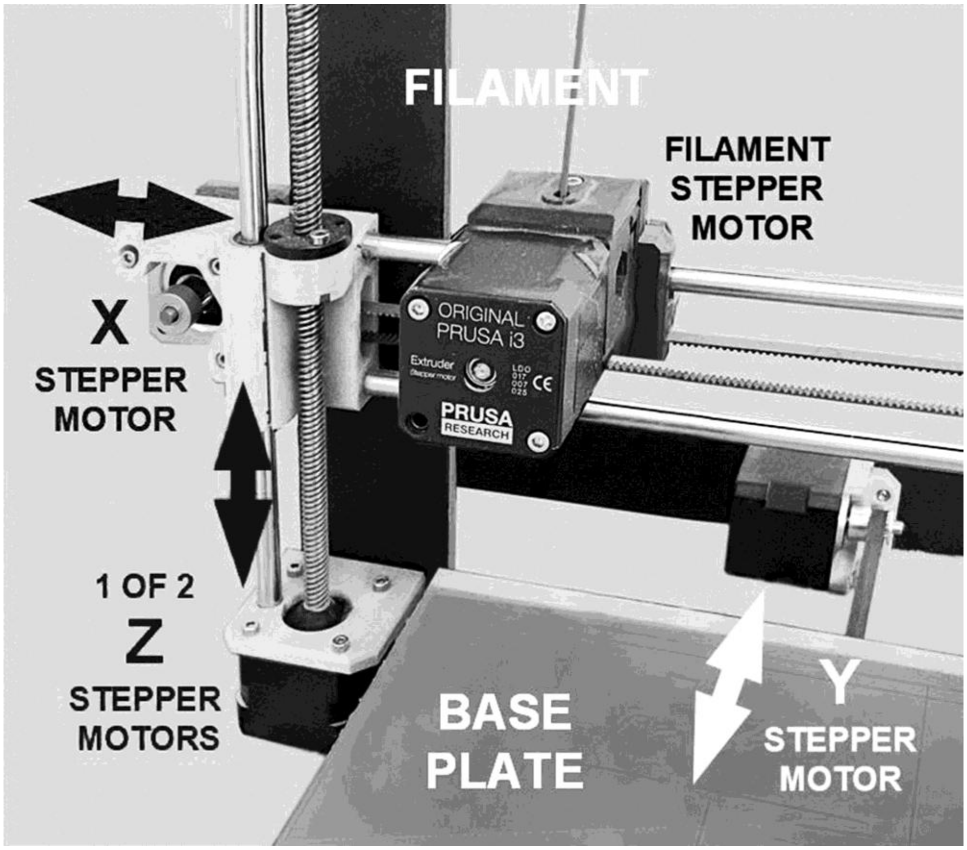

Figure 2 —Simplified pictorial of the X, Y, and Z stepper motors and extruder (filament) stepper motor of the popular Prusa i3 MK3S 3D printer

3.4 G-code

The sequence of CNC motions as well as a number of other machine parameter values are encoded as text instructions called *G-code*. The G-code file is loaded into the 3D printer's memory for each print. It is the complete set of instructions to the printer for print a finished object.

G-code for most home 3D printers today is a customized subset of industry-standard G-code for CNC machines and is controlled by the standard RS-274. The 'G' in 'G-code' refers to Joseph Gerber who developed photoplotters and the basic elements of a programming code to control them. G-code files are sometimes called "Gerber files" for this reason. G-code is also used to specify printed-circuit board layouts and became an industry standard in 1980. The complete set of industry standard G-code commands can be found at **wikipedia.org/G-code**.

The following is a sample of the G-code. A typical file of G-code instructions needed to print an object consists of hundreds of such lines of text that look like the following list:

M140 S120 //	heat the print build plate to 120 degrees
M104 S210 T0 //	heat the nozzle to 210 degrees
G28 //	go home
G29 //	perform auto build plate leveling
G1 E10 F240 //	extrude 10mm of plastic

4. 3D OBJECT DESIGN SOFTWARE

In common practice, the G-code file is created in two steps by separate software programs. The first is 3D design software which creates a computer model of an object to be printed. The result is saved as an *STL* file or an *OBJ* file.

The STL file format (*Standard Triangle* or *Tessellation Language*) is the most common format for 3D printing models. STL is the native file format of CAD software created by 3D Systems. It uses the X, Y and Z coordinates of a series of interconnected triangles (tessellations) to represent the surfaces of the model. All modern CAD software programs will export an STL file. The OBJ format (short for “object”) supports multi-color printing and is used for printing more complex objects. You can find out more about STL and OBJ formats at **3dprintingforbeginners.com/stl-and-obj-files-101.**

The second program is a called a *slicer* because it converts the 3D object model into the layers or slices needed for 3D printing. Unlike the generic 3D object design software, the slicer is specific to each model of printer. The slicer converts the STL file, or other native 3D design output file, into the G-code required by the individual printer. Being printer specific, the slicer’s output G-code is not suitable for sharing between different brands or models of printers.

4.1 3D Design Software

When 3D printing first appeared, hobbyist-level software did not exist. CAD programs then were primarily for mechanical drawing applications. Possibly best known is *AutoCAD* by AutoDesk. For drafting it is a widely-used industry standard. But for designing objects for 3D printing, drafting-oriented CAD packages are awkward.

Later, more image-oriented design programs appeared that were capable of modeling 3D objects. The target audience was, however, the graphics arts and printing industries. This type of 3D design software is best suited for surface rendering and for the creation of organic shapes for artistic applications. Ham 3D printed objects are more typically geometrically shaped. Unless one is interested in creating decorative objects, graphics-oriented software should be avoided. Two useful exceptions are *Mesh Mixer* and *FreeCAD*. Both are free. Used together they are useful for repairing damaged STL files and converting tessellated STL files back into the native “solid” format of a 3D design program. This is often desired to modify an object downloaded as an STL file. A tessellated STL file is not easy to modify directly.

Easy-to-use free hobbyist-level 3D object design software, suitable for most ham projects, is readily available on the internet. There are many professional and semi-professional 3D object design packages available, but most at a price generally beyond the hobbyist's budget. Some of the professional 3D design packages, do however, offer a short-term free trial and some, free student licenses.

Professional-level 3D modelling software is used primarily in industry. Some hams, however, may wish to master one of the professional software programs for career reasons. Industry has a growing need for skilled 3D designers. Or one may wish to use advanced feature of professional design software. Generally, though, these are seldom needed by ham users.

More important, however, in selecting 3D design software is to identify the target audience for which the program was created. Many pure CAD programs, even though they were capable of 3D object modelling, are not targeted for home 3D printing. A careful survey of the internet is, advised before investing the time to become experienced with any 3D design program.

Most ham 3D printing newcomers quickly master the beginning-level 3D design programs, yet also find them entirely satisfactory for long-term ham use. AutoDesk also markets a popular high-level 3D design software package, *Fusion 360*. It has an annual subscription fee. Although powerful and generally easy to use, it has a substantial learning curve. Again, be sure to carefully survey the internet before becoming vested in any 3D design program. One may wish to change early in the 3D printing experience to try different software and to choose the most suitable package.

4.2 Tinkercad

As an illustration of a suitable program for ham 3D printing newcomers, we will examine the *Tinkercad* package. It is perhaps the most widely used 3D object design program for beginners. There are many tutorials for it on the internet. It was developed by AutoDesk and is cloud-based. To obtain a copy, create a free account at **tinkercad.com**. Then with the help of the many videos on the internet, explore the program. Finished projects may be saved on the *Tinkercad* cloud or a local computer for later use or modification, either as a project file or an STL file.

Tinkercad replaces an earlier, slightly more complex, but no-longer-supported intermediate AutoDesk 3D design program, *123d Design* than can still be downloaded from many third-party websites. It is more powerful than *Tinkercad* but also easy to learn. There are also a great many videos and tutorials for *123d Design* on the internet to help the newcomer.

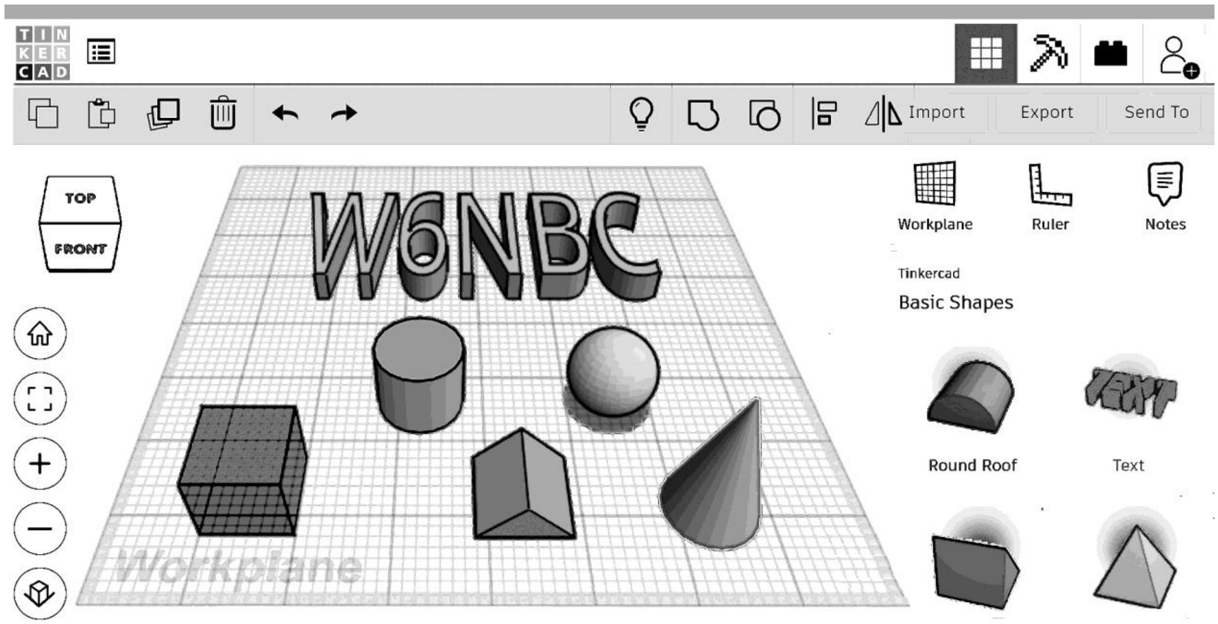

Figure 3 — Workspace of Tinkercad showing "primitive" geometric shapes and text used to create a 3D printer object and an STL file.

3D printed ham project objects are typically combinations of geometric shapes called *primitives* – rectangular solids, cylinders, spheres, cones, pyramids, etc. — that are combined to make complex single objects. One can accurately size, scale, rotate and align objects in *Tinkercad* in units of millimeters or inches. All of the primitive objects can be subtracted from other objects, for example, to make a hole. The workspace is also easily zoomed and rotated for easy viewing.

4.3 Slicer Software

The second step in creating the G-code file for the 3D printer is performed by the slicer software. It converts the X, Y and Z coordinates of the tessellated triangles in an STL file, called a "mesh," into the G-code instructions that the printer needs for each print. Configuration settings for the 3D printer can also be made in the slicer program and included in the G-code file.

A 3D printer is a complex machine, hence there are other functions of the printer that an experienced user may wish to adjust via the slicer program. These settings will be included in the G-code generated by the slicer. It is highly advisable at first to stay with the default settings of the slicer. After printing a test object, the presets of the slicer can be changed to improve the final print quality or to correct errors.

Configuration settings for the slicer software itself can also be changed to suit a particular material or object. Many free test object STL files are available on the web to help make adjustments. (See the directory of STL file websites at the end of this article.) A simple test object, such as a cube, is recommended for initial tests.

For more advanced testing and calibration, the best-known test object is a small tugboat called Benchy, available from **3dbenchy.com**. (See **Figure 4**) It was designed by the Swedish firm, Creative Tools, and is used by more advanced 3D printer users for adjusting software parameters and as a benchmark to compare 3D printers. Other test objects are available online for specific needs, such as minimizing stringing, which is a common cause of poor prints and printer crashes.

Figure 4 — Benchy, a popular advanced user's test object to help fine tune printer settings via a slicer program

4.4 Normal Slicer Adjustments

There are a number of required inputs to the slicer for every object. The working screen of an example slicer program is shown in **Figure 5**. From the top of the selection area at the right of the window:

- PRINT SETTINGS: The user may choose nozzle diameters and print quality modes. For this slicer, settings of DRAFT, SPEED, QUALITY, DETAIL, and ULTRA DETAIL are available. "0.15mm QUALITY (modified)" has been selected. This sets the size of the plastic bead to be extruded and the thickness of the layers or slices. Together these determine the fineness of the print.

- FILAMENT (Plastic Type): Generic PLA plastic has been selected. Slicers contain a list of plastic filaments with the correct temperature settings for the extruder, the heated build plate, and a number of other plastic and printer specific settings.

- SUPPORTS: A 3D printer cannot extrude plastic over empty space with nothing to fuse to. The soft plastic string must be supported by a previously hardened surface. Therefore, if the object has overhanging elements, the slicer can be instructed to add *supports* that can be removed after the print is finished. The printer will, however, *bridge* over small open horizontal spaces, typically on the order of ¼ inch (6 mm). If supports are not requested, the slicer will automatically bridge the small open spaces. ("None" is selected in this example.) Also, if the surface being printed is roughly greater than at least 45 degrees from the horizontal, there is no need for supports.

  In printers with the ability to print in more than one color or with more than one extruder, a special filament designed for supports, most often PVA (polyvinyl alcohol), can be specified by the user. It is water soluble for easy removal.

- IN-FILL DENSITY: Solid shells are printed on the surfaces of the object but a honeycomb-like gridwork is printed internally. The density of the honeycomb is set for each object from 0% (hollow) to 100% (solid). Infill is set to 15% in this example. This saves filament and reduces object weight.

- BRIM: For objects that will have only a small surface touching the build plate, set the slicer to generate a *brim* or *skirt*. It is several rows of plastic bead printed around the periphery of and in light contact with the first layer of the object. The brim increases the contact area with the build plate to help the object stick well and not be knocked loose in the print's higher layers, causing a misprint. A brim also reduces warping. After the print is completed, the brim is snapped off or trimmed away.

- COLOR AND FILAMENT CHANGE: The slicer for a single-extruder printer can be set to halt at a particular slice for the filament to be changed. Afterwards, the print seamlessly resumes. For the slicer shown, the user clicks on SLICE NOW at the bottom of the selection area. This activates a vertical slider to allow examination of all the layers and to choose one for a filament or color change. When the desired layer is identified, the slicer inserts necessary G-code into the design file. (Other slicer software will have a somewhat different method.)

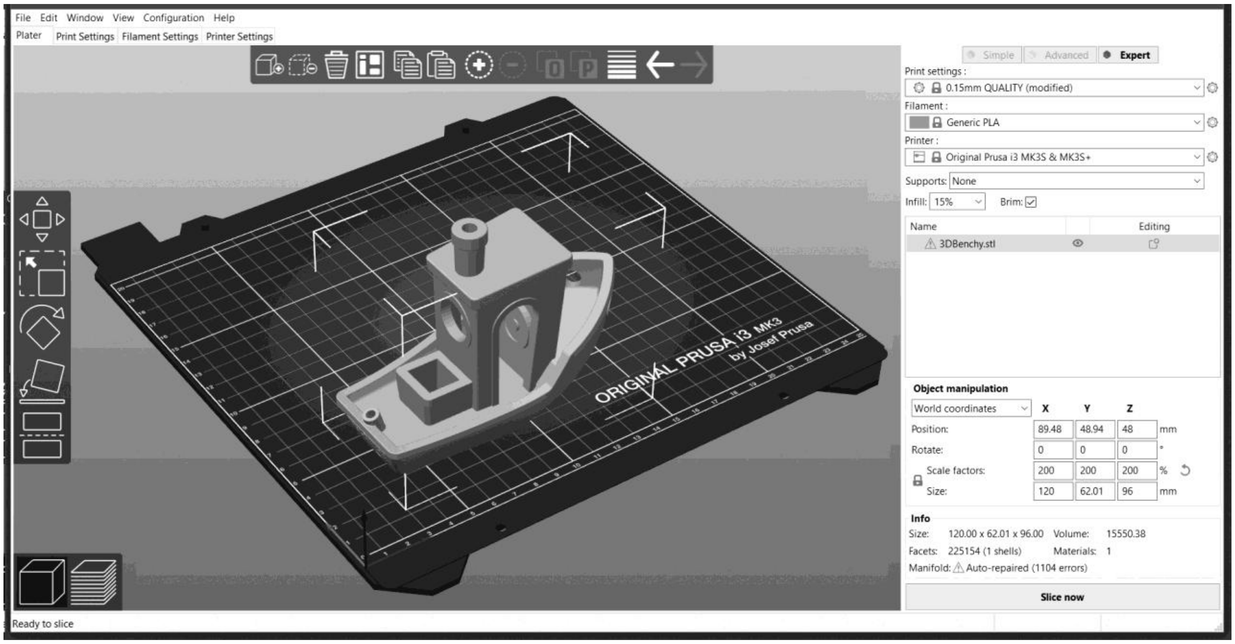

Figure 5 — Workspace of the slicer program for a Prusa i3 MK3S printer with a single "Benchy" test object loaded.

At the top of the workspace on the left side of the window are controls to add, delete, copy and paste, and to arrange multiple objects on the build plate. At the left edge of the workspace are controls to change the position and rotation of the object, set the object on the build plate, and make limited modification to the object. For example, the size or scale may be changed, and the object may be cut into several individual objects. (Values for these parameters are shown in the "Object Manipulation" area at the lower right of the window.)

Finally, user-written G-code commands can be added by the slicer. For example, the user may wish to hear an alarm when the print is complete. However, a familiarity with the general principles of computer coding is needed to introduce custom G-code. One useful easy change to the G-code instructs the printer to complete each object before moving to the next if several objects are being printed at the same time. Each slicer will have a different method for adding custom G-code.

5. CHOOSING A PRINTER

When contemplating the purchase of a 3D printer, like any new equipment there are three key considerations:

1. User experience
2. Price vs. features
3. Manufacturer's reputation

The most worthwhile guide is the internet. YouTube is an exceptionally valuable resource, both for learning 3D printing and for evaluating printers, accessories, and materials. Spend time searching on 3D printing in general, on manufacturer's websites, and in 3D printing magazines and blogs. Magazines often publish lists of the top performing printers at that time. Also look at the comments and reviews from readers.

Ham friends and radio club members who already own 3D printers are also an excellent resource. They have mastered the learning curve and will have meaningful opinions on what to buy and what to avoid. Don't overlook all these local resources.

When choosing a printer or design software, remember that 3D printing is still a moving target. Printers, materials, manufacturers, software and printing methods change continuously. Customer satisfaction is often the only reliable guide in such a rapidly changing technology. Widely-liked performance can easily be more important than the price or brand.

5.1 User Experience

If there are a large number of videos on the printer you are considering, and if the video makers find these reliable and easy to use, they are probably acceptable choices. The same is true for 3D design software and for the reputation of printer manufacturers. User comments and reviews can be very valuable in evaluating their experience with the printer and manufacturer.

5.2 Price vs. Features

Similarly, because of the extremely wide range of 3D printing applications, and because of personal expectations, no generalization can be made on how much to spend on a printer. There are, however, some broad guidelines. Generally, medium-range domestic printers, currently in the $500–1000 range, are the best choice for the majority of ham buyers.

At the low end of the price range, there are a rapidly growing number of less-expensive 3D printers, some in the low-hundred-dollar range. Some are excellent and new models appear frequently. Some companies, including medium-range manufacturers, offer lower-cost and junior-model printers.

Over the long haul, it is important to consider how large an object can be printed. In 3D printing this is called the *print volume*. Low-priced printers generally print only small objects. If, for example, one is printing enclosures for ham projects, lower-priced printers might not be a good choice.

Other important features, often not found on low-priced models, are a heated build plate and automatic build plate leveling. Most experienced 3D printers consider these two features to be necessities. As is common in ham radio, too, when beginning a new hobby, purchasing a "starter model" to get experience at low cost may turn out to be wasted money. Purchasers often soon realize that the best first choice would have better been to go directly for what the experienced participants use — a medium-priced printer. There are some very good small models, but these usually make better second choice printers.

You may be able to save money by purchasing the printer as a kit. Some manufacturers offer their printers as both kit and fully assembled and tested. It may take a fair amount of time to assemble and calibrate a kit, but the experience gained is a strong advantage. If the printer ever requires readjustment, recalibration, or parts replacement, having put it together is of considerable value. Experience also helps avoid unnecessary repairs or part replacement.

Some users also prefer an open-frame style of printer without an enclosure. An enclosure does reduce noise and can help to contain the vapor or smell of the plastic. These, however, are not big problems and easy ways exist to deal with them without restricting accessibility.

5.3 Printer Manufacturers

The following is Wikipedia's current list of "notable" printer manufacturers (Jan 2021) at **en.wikipedia.org/wiki/List_of_3D_printer_manufacturers#0–9**. It illustrates the wide range of 3D printer manufacturers available worldwide. This list changes constantly, so it is important to survey what's available before choosing a printer for ham radio or other hobby needs.

- 3D makeR Technologies – Barranquilla, Colombia
- 3D Systems – Rock Hill, South Carolina, USA
- AIO Robotics – Los Angeles, California
- Airwolf 3D – Costa Mesa, California, USA
- Aleph Objects – Loveland, Colorado, USA – (Lulzbot printers)
- Carbon – Redwood City, California, USA
- Cellink – Boston, Massachusetts, USA
- CRP Group – Modena, Italy
- Creality – Shenzhen, China
- Desktop Metal – Burlington, Massachusetts
- envisionTEC – Gladbeck, Germany
- Formlabs – Somerville, Massachusetts, USA
- Fusion3 – Greensboro, North Carolina, USA
- Geeetech – Shenzhen, China
- HP Inc. – Palo Alto, California, USA
- Hyrel 3D – Norcross, Georgia, USA
- Kikai Labs – Buenos Aires, Argentina
- Kudo3D – Dublin, California
- M3D – Fulton, Maryland, USA
- Made In Space, Inc. – Mountain View, California
- MakerBot – New York City, New York, USA
- Materialise NV – Leuven, Belgium
- MarkForged, Massachusetts, United States
- Mcor Technologies Ltd – Dunleer, Ireland
- Printrbot – Lincoln, California, USA
- Prusa Research – Czech Republic
- Renishaw plc - Wotton-under-Edge, Gloucestershire, UK
- Robo3D – San Diego, California, USA
- Sciaky, Inc. – Chicago, Illinois, USA

- Sindoh – Seoul, South Korea
- SLM Solutions Group AG – Lübeck, Germany
- Solidoodle – New York City, New York, USA (Closed)
- Solidscape – Wilton, New Hampshire
- Stanley Black & Decker – New Britain, Connecticut, USA (Manufactured by Sindoh – South Korea)
- Stratasys – Minneapolis, Minnesota, US

6. PLASTIC (FILAMENT) FOR 3D PRINTING

6.1 Characteristics of Common Plastics used for 3D Printing

Essential to the hobbyist entering 3D printing is a familiarity with the commonly available plastic filaments. The best choice for each project will depend on the nature of the project. **Table 1** is a quick guide, sorted by ease of printability. This is the biggest concern for many new 3D hobbyists. The two filaments that stand out for printability are PLA and PETG. This accounts for their popularity and they are good choices for beginners. With experience, however, the other common filaments become easy to use.

Price is also a factor. PLA, made from corn starch or sugar cane, is the clear winner. Though it is the favorite of most newcomers, it is still a good choice for projects not requiring the properties of more expensive and more difficult to print plastics. PETG, the other frequent beginner's choice, is a little more expensive, less brittle and therefore more durable. It also tolerates higher temperatures. ABS is also liked by many 3D printer owners for other properties. and is not difficult to use with modest experience.

Table 1
Printing Properties of 3D Filament Plastics

	PRINTABILITY	*$ / kg*	*STRENGTH*	*RIGIDITY*	*DURABILITY*	*MAX. TEMP.*
PLA	9	10-40	65	7.5	4	52C/126F
PETG	9	20-60	53	5	8	73C/163F
ABS	8	10-40	40	5	8	98C/208F
NYLON	8	25-65	62	5	10	95C/203F
CARBON FIBER FILLED	8	30-80	46	10	3	52C/126F
POLYPROPYLENE	8	60-120	32	4	9	100C/212F
WOOD FILLED	8	25-50	46	8	3	52C/126F
ASA	7	35-40	55	5	10	95C/203F
METAL FILLED	7	50-120	25	10	4	52C/126F
FLEXIBLE	6	30-70	35	1	9	65C/149F
HIPS	6	25-35	32	10	7	100C/212F
POLYCARBONATE	6	40-75	32	6	10	120C/248F
PVA	5	40-110	78	3	7	75C/167F

Websites such as **www.simplify3d.com/support/materials-guide/properties-table** and **all3dp.com/1/3d-printer-filament-types-3d-printing-3d-filament** also provide a lot of information about the properties of different plastics for 3D printing.

6.2 Resistance to Ultraviolet Light

Of particular concern to hams is the plastic's resistance to the ultraviolet light (UV) in sunlight. Many ham 3D printed objects will be used outdoors and experience long-term exposure to sunlight. Without exception, all sources agree that the best plastic for UV resistance is ASA (Acrylonitrile Styrene Acrylate). It is a relative of common acrylic plastic. Acrylics are virtually impervious to UV. This is a chief reason why they are used for outdoor signs. ASA is somewhat more difficult to print with and is more expensive, but for ham projects exposed long term to sunlight it is the best choice. With a little experience, ASA is easy to print with. Table 23.7 gives a general picture on the UV properties of the common 3D printing plastics that was compiled by W7SX.

Table 2
UV Resistance of 3D Printing Plastics

Material	*UV Resistance*
ABS	Fair
Acrylic	Good
Polycarbonate	Fair
Polyethylene	Poor* – Fair
Polypropylene	Poor* – Fair
Polystyrene	Poor – Fair
PTFE	Very Good
PVC (plasticized)	Fair

*Basic UV resistance can be improved with additives
From "Using Plastics for Dielectrics," Robert Zavrel, W7SX, *QEX*, January/February 2021

Another source is this abbreviated summary for other common 3D plastics: **3dprinterly.com/best-filament-for-outdoor-use-is-pla-suitable**.

A useful tip for adding outdoor UV protection is to apply a varnish or lacquer. A suitable choice is Krylon Clear Coatings Aerosol. It dries in minutes, is moisture-resistant, and has a non-yellowing surface. It is widely available, including online sources.

PLA (Polylactic Acid): PLA is a biodegradable plastic made from renewable resources such as sugar cane or corn starch. Just because it is biodegradable doesn't mean it won't fare well in sunlight. It may become more brittle and lose its rigidity, but for the most part it will keep its main form and strength as long as it is not used for a high-strength item such as a handle or mount. This is discussed further in the author's article at **3dprinterly.com/why-does-pla-filament-get-brittle-snap-fixes-solutions**.

PLA in its purest form is more resistant to UV. Avoid using dark-colored PLA because it will attract heat and turn soft. Even more surprising, since PLA is made of organic products some animals have been known to try to eat PLA objects.

ABS (Acrylonitrile Butadiene Styrene): ABS plastic has many advantages compared to PLA when it comes to outdoor use, mainly that it is a non-biodegradable plastic. ABS can withstand sunlight for a longer time as it is much more temperature resistant than PLA. Due to its rigidity and good tensile strength, it is a good option for short term outdoor use. ABS in its purest form, which is clear, won't absorb energy from UV radiation.

The black coloration of ABS DWV drain, waste and vent (DWV) pipe is due to a carbon filler and thus it is not suitable for RF applications. Carbon added to DWV pipe makes ABS, which is not naturally UV resistant, suitable for outdoor use. However, black ABS 3D printer filament is not carbon filled.

PETG (Polyethylene Terephthalate Glycol): PETG, a glycol-modified version of normal PET, is the most durable under long exposure to UV radiation. It is a less rigid and more flexible material than ABS plastic. Its flexibility allows it to expand and contract according to the temperature conditions of long exposure to outdoor.

PETG's smooth finish helps it to reflect most of the radiation falling on the surface and its transparent appearance does not hold heat energy from the radiation. it is more prone to wear when used outdoors due to its soft surface.

6.3 RF Power Handling Capacity of Plastics

Another important factor in choosing a 3D printing plastic for ham projects is how well a plastic will work in a high RF environment. The property is called *dissipation factor* (*DF*). It is a measure of how much the materials dissipate RF as heat. The higher the DF, the lower an RF field strength the plastic will tolerate before melting. Materials with a high DF are referred to as "lossy". It is important to consider both the physical and the electrical properties in selecting a 3D printing filament for a ham radio project.

Dissipation factor is also referred to as the *loss tangent* (*tan δ*). It is the reciprocal of the ratio of the insulating material's capacitive reactance (X_C) to its electrical resistance (R). Stated another way, it is the ratio of permittivity (ε) to conductivity (σ). **Table 3** lists the DF of common plastics.

Table 3
Dissipation Factor of Common Plastics

Plastic	*Dissipation Factor (tan δ)*	
	1KHz	1MHz
PTFE (polytetrafluoroethylene) Teflon	<0.0001	<0.0001
LDPE (low density polyethylene)	0.0003	0.0003
PP (polypropylene)	0.0003	0.0003
PLA (polylactic acid)	0.0003	0.0004
HDPE (high density polyethylene)	0.0005	0.0005
PS (polystyrene) Styron	0.0005	0.0005
PVC (polyvinylchloride)	0.013	0.006
PC (polycarbonate) Lexan	0.0015	0.01
PI (polyimide)	0.0025	0.01
PET (polyethyleneterephthalate) Mylar	0.005	0.016
PMMA (polymethylmethacrylate) Plexiglas, Acrylic [ASA]	0.04	0.03
Nylon6 (polycaprolactam)	0.016	0.036

Table 3 is organized from lowest to highest dissipation factor. One or two plastics not commonly used for 3D printing are included to illustrate the general use of dissipation factor in selecting plastics for electronic applications. For example, at the top of the list, notice the excellent performance of Teflon or PTFE. Also having a low DF, PLA (polylactic acid) and PP (polypropylene), both common 3D printing plastics, would be a good choice for a coil form used at higher power. PET polyethylene terephthalate, the second most popular 3D printing plastic, is not as good. Lastly, ASA, with its good UV resistance and Nylon with its strength, have poor dissipation factors.

7. THE BUILD PLATE

7.1 Build Plate Surfaces

Most printers have a base aluminum build plate. Printing is not done directly on the base build plate. An additional surface is added to the base. These are common surface materials:

- A sheet of borosilicate glass
- A self-adhesive sheet of PEI (polyimide) plastic (the best choice)
- Various surface treatments by the manufacturer, such as powder coating
- A layer of common blue painters' tape
- A layer of Kapton (polyimide) tape.

Borosilicate glass plates, PEI sheets, and Kapton tape for 3D printers are available online. Blue painter's tape is a common hardware item.

A removable flexible steel sheet is another common added print surface. On some printers, magnets are embedded in the build plate to hold the sheet in place, on others it is held by clips at the edge. A self-adhesive PEI plastic sheet is then typically applied to the steel. A removable flexible sheet makes the removal of printed object easy: a small flex and the printed parts pop off. Tightly adhered objects can be difficult to remove from a fixed build plate, increasing the risk of damage to the build plate.

7.2 Build Plate Adhesives

In most cases it will also be necessary to apply an adhesive to the build plate so that the first layer of plastic sticks firmly. Problems in the first layer are the cause of a high percentage of failed prints. Poor adhesion can also allow objects to warp, especially with some plastics, such as ABS. Once printing proceeds past the first layer the soft plastic readily fuses to a previously deposited plastic.

Table 4
Build Plate Adhesives

Adhesive	Use with	Advantages	Disadvantages
Glue stick	ABS, Nylon and most others	Inexpensive Easy to apply	May be a little difficult to clean off the build plate
Hair spray	PLA, PETG, ASA	Inexpensive Makes a thin and even layer	Other printer parts may be over-sprayed
ABS slurry	ABS, ASA	Highly recommended with ABS	Time to prepare the ABS slurry
Blue painter's tape	ABS, PETG, TPU	Inexpensive Easy to apply/remove	Not durable May have to be reapplied after every use
Kapton polyimide tape	PLA, TPU, ASA, HIPS	More durable than painter's tape Gives a smooth surface to item	Difficult application May have to be reapplied after every use
PEI sheet	Any plastic	Very reliable adhesion Useable multiple times Clean with soap & water	Prints may stick firmly to the sheet

The two most-used adhesives are glue stick (PVA) and hair spray (PVP). Both are water soluble. Before applying any adhesive, clean the surface with isopropyl alcohol (most common) and/or hot water. Occasionally also clean the surface with acetone.

If hairspray is used, be careful not to over-spray onto other parts of the printer. If the printer has a removable steel print bed sheet, remove it to apply hair spray. Hair spray is easily removed with soap and water.

For ABS plastic, due to its tendency to shrink as it cools, a special adhesive is highly recommended, variously called ABS slurry or ABS juice. Shrinkage is a natural property designed into ABS in the early days of plastic injection molding to allow molded parts to easily fall out of the mold. ABS glue or slurry is made by simply dissolving scraps of ABS in acetone, in which ABS is very soluble. The glue is then brushed or wiped onto the build plate before the print. ABS glue also works moderately well with ASA plastic.

7.3 Extruder Height Adjustment

The instruction manual for every printer includes the steps to adjust the working height of the extruder during a print. However, before it can be set, the mechanical geometry of the printer must have been carefully aligned. This is called the *X, Y, Z calibration*. Follow the manufacturer's calibration instructions meticulously. This cannot be overemphasized.

The next adjustment that must be correct before extruder height can be set is *bed leveling*. It is only a manual adjustment on lower-cost printers; it is automatic on others. Many experienced 3D hobbyists consider automatic bed leveling essential and it is highly recommended.

A brief summary of mechanical bed leveling is available at **3daddict.com/beginners-guide-3d-printing-tips-tricks**. Even printers with automatic bed leveling are usually set up this way initially:

> "Move the nozzle (extruder) over the home area and zero the printer's Z Height. [When the adjustment is correct] A sheet of computer printer paper should be able to slide in between the nozzle and print surface and a slight resistance of the nozzle on the paper felt. The paper should barely be able to be moved back and forth without buckling or folding due to friction. Perform this for all the corners and the center of the built plate."

To visualize why extruder height adjustment is critical, see **Figure 6**. To cause the soft plastic to positively adhere to the build plate and to subsequently fuse to a previously extruded layer of plastic, the tip of the extruder's nozzle must flatten the bead, called *squish*. The gap between nozzle tip and the bed or object must be roughly half the height of the diameter of the extruding plastic bead as illustrated in Figure 6.

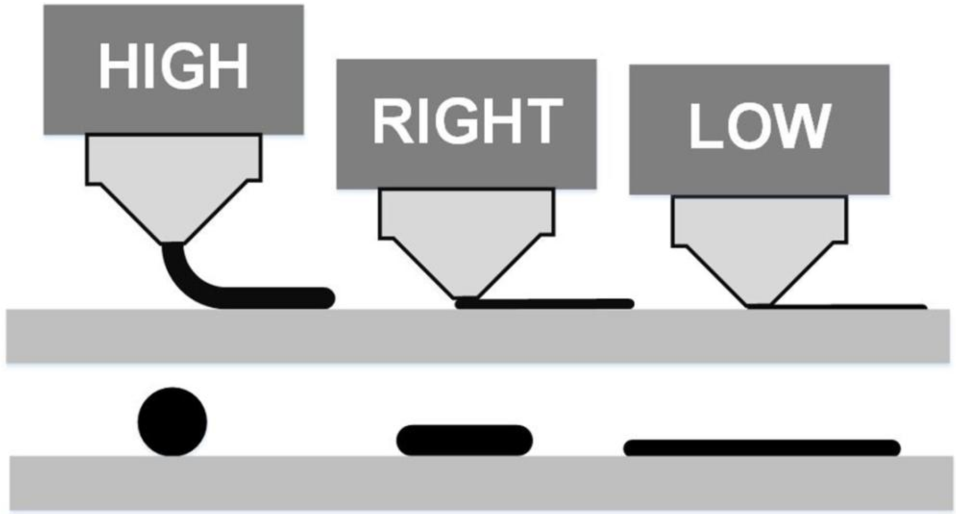

Figure 6 — "Squishing" of the extruding plastic bead: (left) No squish; (center) Correct amount of squish; (right) Too much squish. (not-to-scale)

If the extruder height is too high, the bead won't be squished. The correct amount of squish is a deposited bead twice and wide and half as high. With the extruder too low the bead will be squished too much. Recognizing a properly squished bead is an essential 3D printing skill and requires close attention.

It will be immediately evident when the printer begins the first layer. The single-bead brim or skirt the printer first prints around the object is the best guide. Gaps in the bead are a strong indication that the extruder is adjusted too low. Beads that do not stick indicate too high an adjustment.

Most printers have a live adjustment that can be invoked from the front panel during a print to make small corrections to the extruder height. Many printers also have a first layer calibration adjustment option on the control panel. It will cause the printer to print patches of adjacent beads for inspection. Become very familiar with first layer calibration of extruder height.

For initial prints with a printer or new plastic, experiment with this adjustment. Choose simple objects at first. It is the most important adjustment. Once set well, it will rarely need to be changed and successful prints in most plastic types will become commonplace. Many of the websites that offer free STL files (see the directory below) have extruder or first layer test objects to print.

8. A TYPICAL PRINT SEQUENCE

The following basic steps are followed for every print. This is a reference for the newcomer and also highlights some tips for all experienced 3D printers. This particular sequence is for a very popular full-featured, mid-price FDM printer, a Prusa i3 MK3s equipped with a removable flexible steel build plate sheet and fitted with a self-adhesive PEI plastic surface.

1. Load the object's G-code file into the printer from an SD card, flash memory, or via USB from a separate computer.

2. Turn on the printer and let it go through its start-up sequence.
3. Clean the build plate surface with isopropyl alcohol and or hot water. Four-inch surgical gauze squares make excellent wipes. Inexpensive alcohol dispenser bottles are ideal for keeping alcohol handy. Occasionally clean the surface more thoroughly with acetone.
4. If the printer has a removable flexible steel plate on the build plate, look for anything trapped under it that may cause a "bed leveling error".
5. From the printer's control panel, raise the extruder to near the top of its travel. Activate "pre-heat" for the type of plastic to be used. This will allow space under the extruder and time for the heating plastic to "ooze." Brush the tip of the nozzle continuously with a small brass or stainless-steel wire brush.
6. Select the G-code file displayed on the control panel to activate the sequence. The printer will wait until both the proper bed and the extruder temperatures have been reached. Continue to brush off oozing filament as the print cycle begins.
7. The printer will begin by going through a nine-point automatic bed levelling sequence. Then it will move the extruder to the home position and begin extruding a *purge strip* near the edge of the print area. The purge strip allows the flow of hot plastic to stabilize. Become familiar with what the purge strip looks like. It is a good indication that all is working correctly. Otherwise, stop the print and begin again.
8. The printer will next print a "skirt," a double plastic bead, around the perimeter of the first layer of the object to be printed. Pay close attention to the bead to see that it looks normal and that unwanted fragments of plastic are not being carried along with it. Carefully remove any fragments without disturbing the print.
9. If the printer's control panel displays the height of the extruder, note the value. The typical first-layer height for the common nozzle will be 0.2 mm. It is a recommended practice to remain present for the entire first layer. A good percentage of printing problems occur during the first layer. Once the extruder height changes to a higher layer, e.g. 0.35 mm, the printer may then be left unattended. Check back regularly, however. Many users install webcams or video baby monitors on their printer to watch for misprints and jams.
10. Remove the part when printing finishes. If the printer's build plate is equipped with a removable flexible steel sheet, removing the part should be easy. Just remove and flex the plate and the part(s) will pop off. If a removable sheet is not used, be careful when removing parts because it is easy to damage the surface of the build plate.
11. Clean up the printed part. Needle-nose pliers and a small screwdriver are handy when removing strings, flashing, and supports which are normally removed with a hobby knife or a small file. A short blast of hot air from a heat gun is good for removing fine strings.

9. FREE STL FILES TO PRINT

9.1 Links to STL Websites

The following is a reasonably complete list of websites that offer free STL files to print as of Jan 2021 from **www.youtube.com/watch?v=eIfDog1UUJc&t=51sYouTube**. The number of free STL files available on the internet is truly immense and growing daily. Not all are perfect; some will need adjustment, but many are excellent and fully printable. The first two entries on the list are the most popular websites.

www.stlfinder.com
www.thingiverse.com
www.models-resource.com
nasa3d.arc.nasa.gov/models
zheng3.com/forge/index.php?id=-4
polar3d.com/index.html
cults3d.com/en
www.myminifactory.com
impression3d.laposte.fr/en
pinshape.com
www.3dprintmakers.com
www.Tinkercad.com
www.stlhive.com
www.rascomras.com
www.shapetizer.com
fab365.net
www.rinkak.com/jp
www.3dagogo.com
3dcollectible.com
libre3d.com
repables.com
library.zortrax.com
free3d.com
www.threeding.com
www.redpah.com
3dwarehouse.sketchup.com
sketchfab.com
de.3dexport.com
3dprint.nih.gov
www.treatstock.com
www.youmagine.com
www.punishedprops.com
digilab.dremel.com/resources
dogpile.com