



# 3D printing

## IN TECHNOLOGY AND ENGINEERING EDUCATION

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*Students may be enticed to pursue STEM-based careers by just having a 3D printer in the classroom, but the fruit of this educational tree truly begins when you start printing.*

In the past five years, there has been tremendous growth in the production and use of desktop 3D printers. This growth has been driven by the increasing availability of inexpensive computing and electronics technologies. The ability to rapidly share ideas and intelligence over the Internet has also played a key role in the growth. Growth is also spread widely because Internet communities allow people to share designs that can be manufactured and reengineered without leaving their desks. President Obama even recognized this technological change when he stated, “3D Printing is the wave of the future,” in his 2013 State of the Union Address (Obama, 2013). Educational institutions at all levels are beginning to recognize the value of 3D printing technology and have begun to incorporate these machines into their laboratories. A 3D printer facilitates the interactive instruction in technical concepts and systems consistent with the nation’s focus on science, technology, engineering, and mathematics (STEM) learning initiatives. President Obama has proposed new manufacturing tax breaks that will create more robust research and development spending. This shift in focus is aimed at advanced manufacturing technologies, including 3D printing, to bring a competitive edge back to America (Foroohar and Saporito, 2013).

The purpose of this article is to share introductory information about 3D printing, how 3D printing can be used in the technology and engineering classroom—especially how this teaching and learning artifact directly relates to learning standards—and to share examples of hands-on artifacts that can be designed and prototyped in the classroom.

While 3D printing is rich in its connections with mathematics and science, the authors have limited this article to its connections with *Standards for Technological Literacy: Content for the Study of Technology (STL)* (ITEA/ITEEA, 2000/2002/2007). The authors have focused solely on *STL* because the nature of this article lends itself to overall understanding of 3D printing and its role as a new teaching and learning artifact for the technology and engineering classroom. 3D printing can help to meet the benchmarks found in 15 of the 20 *STL* standards without any curricular hesitations from the technology and engineering teacher (*STL* 1-4, 6-14, 17, and 19).

The *STL* standards and benchmarks that can be addressed through the use of 3D printing as a teaching and learning artifact will, of course, depend upon the curriculum that is in place at each teacher’s school, but overtly, 3D printing may help to meet nearly all of the *STL* standards. For purposes of this article, the authors have provided examples of how 3D printing can be used to help meet the first four:

- *STL* 1: The characteristics and scope of technology (benchmarks include people and technology; tools, materials, and skills; creative thinking; human creativity and motivation; product demand; rate of technological diffusion; and commercialization of technology).
- *STL* 2: The core concepts of technology (benchmarks systems, resources, requirements; trade-offs; controls; and optimization).
- *STL* 3: The relationships among technologies and connections between technology and other fields (benchmarks knowledge from

other fields of study; knowledge, protection, and patents; and technological knowledge and advances of science and technology and vice versa).

- *STL 4*: The cultural, social, economic, and political effects of technology (benchmarks helpful or harmful; unintended consequences; attitudes toward development and use; ethical issues; and influences on economy, politics, and culture).

## THE EVOLUTION OF 3D PRINTING TECHNOLOGY

The 3D printer is an adaptation of Computer Numeric Controlled (CNC) machines that were first invented in 1952 when researchers at Massachusetts Institute of Technology wired an early computer to a milling machine (Gershenfeld, 2012). Computer-controlled machines have improved the reliability and accuracy of manufacturing because of the precise control and repeatability that computer programming offers. The initial CNC milling techniques were followed by machines using lasers and water-jet cutting. All of these techniques began with raw stock material and then removed material until the desired specifications were reached. In the 1980s, fabricators transitioned from the removal to the addition of material in the fabrication process; a technique called additive manufacturing (Gershenfeld, 2012). Additive manufacturing allowed the fabrication of more complex designs than techniques that relied on the removal of material from raw stock. Additive manufacturing has become a breakthrough for companies that specialize in the design of new products by allowing rapid-prototyping. 3D Systems, Stratasys, Epilog Laser, and Universal were early companies that produced rapid-prototype machines for sale. The models produced by these companies sold for anywhere from \$30,000 to \$400,000. The high cost made it rare to find this technology in educational institutions.

## GROWTH AND DISSEMINATION OF 3D PRINTING TECHNOLOGY

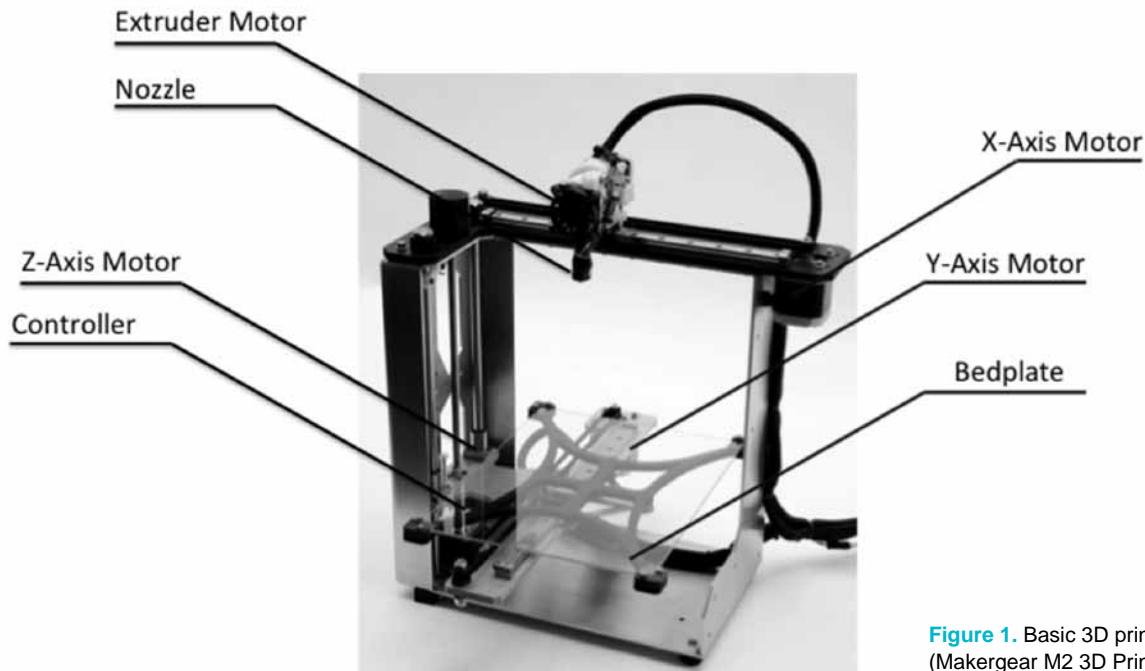
In the last five years, the use of 3D printing technology has grown dramatically. RepRap Ltd., created by Dr. Adrian Bowyer, was the first to make affordable 3D printers available to the public. RepRap based the production of new 3D printers on parts that were printed by another 3D printer. Dr. Bowyer was also instrumental in establishing the open source nature of the 3D printing revolution. RepRap released its first model, the Darwin, in 2007, its second model, the Mendel, in 2009, and several other models in the years that followed. Makerbot, an offshoot of RepRap, and a few other individuals in New York City, began selling 3D printer kits and complete 3D printing machines in 2009. Demand for these models grew so quickly that the producers actually solicited customers to print parts to keep up with sales. A number of other companies have entered the 3D printing market in recent years (Gershenfeld, 2012). Table 1 shows a variety of 3D printer manufacturers that provide different printing technologies to satisfy various user requirements.

## 3D PRINTING ETHICS

Although the rapid growth and expansion of 3D printing technology has been a hot topic in the press this past year, not all of the information presented has been positive. For example, 3D printers have been linked to the design and manufacture of unregulated firearms. The 113th U.S. Congress responded quickly to the firearm issue by introducing an amendment to H.R. 1474 that extends coverage of, and exemptions under, the Act to undetectable firearms, firearm receivers, and ammunition magazines. This resolution specifically prohibits the manufacture, importation, sale, shipment, delivery, possession, transfer, or receipt of undetectable firearms, firearm receivers, and ammunition (Israel, 2013).

Company Name	Model	Assembled	Technology	Max Printable Area (mm)	Cost
Solidscape	3Z Studio	Yes	Smooth Curvature Printing	152x152x51	\$24,650
SolidModel USA	Solido SD300 Pro	Yes	Selective Heat Sintering	160x200x135	\$9,995
Asiga	Freeform Pico Plus27	Yes	Sliding Separation	35x21.8x75	\$8,990
Formlabs	Form 1	Yes	Stereolithography	125x125x165	\$3,299
Fablicator	Fablicator	Yes	Fused Filament Fabrication	178x178x178	\$3,000
Makerbot	Replicator 2	Yes	Fused Filament Fabrication	285x153x155	\$2,199
Ultimaker Shop	Ultimaker	DIY Kit	Fused Filament Fabrication	210x210x210	\$1,598
Makergear	M2	DIY Kit	Fused Filament Fabrication	203x254x203	\$1,450
RepRapPro	RepRapPro	DIY Kit	Fused Filament Fabrication	210x190x140	\$1,129

**Table 1. 3D Printer Manufacturers**  
([www.3ders.org/pricecompare/3dprinters/](http://www.3ders.org/pricecompare/3dprinters/))



**Figure 1.** Basic 3D printer components.  
(MakerGear M2 3D Printer, makergear.com)

Another issue surrounding 3D printing and its growth from the open-source environment lies in intellectual property law. The most popular open-source site available right now is located at Thingiverse.com. Thingiverse is a website that hosts a platform for members all over the world to post digital part files to create real objects with 3D printers. Recently, Thingiverse was forced to remove several users from its website due to the posting of copyrighted material, including characters from the movie *Star Wars* and the *Iron Man* helmet, just to name a couple of items that were illegally posted (Greenberg, 2012). John Hornick, a partner at Finnegan, Henderson, Farabow, Garrett & Dunner law firm in Washington, DC, said at the recent Inside 3D Printing Conference that 3D printing could bring the “demise of intellectual property” for companies that sell unique, manufactured objects that can be easily reproduced in a 3D printer (Neagle, 2013). As the ethical boundaries with 3D printers are beginning to surface, it is important for educators to remember that Federal laws are in place to protect both the safety of civilians and the intellectual property rights of individuals and businesses. 3D printers are an excellent tool to help teach students the many different disciplines of engineering design, but it is advised that you make sure students are not engaging in illegal activities.

### 3D PRINTER BASICS

The 3D printer integrates many technical systems into one compact machine, and mastery of the technology requires the

understanding of a number of different systems. The printer components of primary importance are the extruder motor and nozzle, bedplate, X, Y, and Z-axis motors, pulleys and belts, frame, and the electronic controller circuit board. 3D printers can have many different mechanical configurations to control the movement of primary components, but the basic principles remain the same across configurations. The common 3D printer components are shown in Figure 1.

In this example, the extruder and bedplate are mounted on the frame and controlled by stepper motors, pulleys, and belts. The X-axis motor drives the extruder to move along the X-axis. The bedplate is driven by the Y-axis motor and moves the Y-axis. The extruder uses a separate stepper motor to drive the plastic into a heated barrel, which melts the plastic and forces it through a small opening at the tip of the nozzle onto the bedplate. An entire layer of the part being printed is extruded onto the bedplate before the Z-axis motor drops the bedplate down a fraction of a millimeter to begin the next layer. This process is repeated until each layer of the 3D model has been printed. An onboard processing controller operates the heated nozzle, bedplate, and stepper motors. The controller translates a computer file into mechanical operations that direct the components of the machine accordingly to physically create the part.

3D printing presents a number of learning curves of varying degrees, but the open-source nature and proliferation of online

communities provides a wealth of resources to climb those curves. RepRap's Wiki page contains the basics, including a glossary of 3D printing terms and forums that contain a wide range of discussion topics. It also offers content for the more advanced user, including instructions on how to build open-source 3D printers, modeling software instructions, and a variety of printer configuration settings to maximize the quality of printed parts. Websites like Makerbot's Thingiverse.com contain thousands of digital part files and projects that can easily be downloaded and printed. Today, open-source machine designers have made plans available for extremely high-quality 3D printers that cost less than \$800 complete with off-the-shelf components and 3D printed parts. However, it is always wise to remember that anyone can post information on the Internet, and solutions for one type of 3D printer may not be correct for other printers.

## 3D PRINTING BASICS

A series of operations are required to create 3D objects. First, a data file representing an object must be created with drafting software or downloaded from the Internet. Then the file must be transferred from your computer to the printer. It is easiest for a beginner to find part files on the Internet. Most part files that are used in 3D printing are stereo-lithography files, or STL files for short. More advanced 3D printer users can create parts using various 3D modeling software and exporting them in STL file format.

Once an STL file has been obtained, it must be imported into a slicing program that will generate a G-Code file, a type of language used with CNC machines. There are several open-source slicing programs available on the Internet, including Skeinforge and Slic3r. Slicing programs contain a number of settings that will generate G-Code compatible with the 3D printer. There is also a wide range of settings that affect the material composition of the part, including, but not limited to, the number of solid and/or perimeter layers, the infill density, extruder and/or bed temperatures, fan settings, machine travel speeds, etc. These settings will vary from program to program, but all will affect structural quality of the part. Experimenting with the various settings allows the user, both teacher and students, to learn by doing and determine through experience how optimum prints can be obtained. For most applications, high-quality parts can be produced using three perimeters, three solid layers, and a 25% infill while conserving plastic and reducing printing time.

## INTERACTIVE CLASSROOM LEARNING

Students may be enticed to pursue STEM-based careers by just having a 3D printer in the classroom, but the fruit of this educational tree truly begins when you start printing. There are two distinct modes through which a 3D printer can be used in a classroom setting. The 3D printer itself represents the combination of a number of engineering disciplines into a single machine. The 3D printer gives the instructor a tangible example of how the integration of multiple technical systems can synergize to produce physical objects. Often physics and engineering principles are taught from the strictly theoretical perspective. Students learn about the physical and engineering realities through mathematical abstraction. The 3D printer allows an educator to produce physical models that students can touch, feel, and ultimately test under different physical constraints. For example, a class could print bridges and test the differential load-bearing qualities of different structural designs.

### *Application 1: Mechanics*

A 3D printer can create a wide range of simple machines like gears or pulleys and even screws. Specifications of gears, pulleys, and integrated systems of multiple gears or multiple pulleys can be discussed in class before they are produced. This process gives students a more realistic view of the design and production phases of manufacturing. If done correctly, the process can spark students' intellectual curiosity by creating anticipation between the time the parts are discussed and the time they actually appear. Then the system of gears or pulleys can be assembled and put to use in classroom lab activities.

### *Application 2: 3D Modeling Skill Enhancement*

The 3D printer can also enhance classes that are based around 3D modeling software. Most 3D modeling classes are taught in computer labs and rarely result in the creation of the physical models. This can lead to a disconnection between creations in a digital environment with constraints encountered in the physical world. If components are only designed in 3D modeling software, students do not recognize the complications that arise when turning those models into a physical part. Whether the problems stem from manufacturability or tool access for assembly, sometimes the lack of having a physical part for inspection can hinder the students' learning. A 3D printer can produce uniquely designed parts that a student can physically inspect. This inspection will have an immediate effect on the overall design process. Students will be able to see their mistakes in the part, make adjustments in their digital models, and print out another part to verify that the corrections they made



**Figure 2.** Solar Powered Stereo v2.  
([www.thingiverse.com/thing:42586](http://www.thingiverse.com/thing:42586))

to the model are sufficient. This continuous process of design, creation, and inspection helps accelerate students' engineering skills and capabilities.

### **Application 3: Custom Projects**

Technology and engineering education departments engage students in a wide variety of learning activities. Whether students are learning about mechanical systems, product design and fabrication, or electrical systems, the versatility of a 3D printer can enhance all of these activities. Electrical systems usually require some sort of work board or unique housing. Prefabricated housings for projects might be hard to find, but the 3D printer can be used to produce them. The 3D printer can produce customized nonconductive boards or housing for electrical circuits. Simple project boards for series and parallel circuit projects can easily be created with a 3D printer.

The printer is especially useful for more complex projects. At Illinois State University, a group of students are utilizing a 3D printer to produce all of the custom housing components for solar-powered stereos. The solar powered stereo is shown in Figure 2.

This particular project integrates many technical concepts and skills into a fun and interactive project. Acquiring all of the unique housing components would require much more time and resources without the utilization of a 3D printer. Plus, the students will be able to keep the stereos when the project is complete. The free plans for this project can be found online by searching for "Solar Powered Stereo v2" on Thingiverse.com.

Technology and engineering teachers who are involved with robotics and open-source programming interfaces like Arduino can use a 3D printer to dramatically expand the possibilities of their projects. Custom parts for these projects can be created in a matter of hours with a 3D printer. There are many of these projects, both simple and more complex, available for free on the Internet.

## **THE ULTIMATE 3D PROJECT**

The ultimate 3D project is to build a 3D printer. There are many options available depending on skill level and interest. Easier options include purchasing a kit from companies that specialize in 3D printers. The kits are moderately affordable, usually between \$1,200 and \$2,500, and come with all the components right out of the box. Assembling a 3D printer from these kits will provide students with many benefits. They will learn team-building skills, the ability to read and follow complex technical directions, as well as learning about the 3D printer inside and out. A more challenging option is to build a 3D printer from open-source designers who publish their plans on the Internet. These specialists in the online 3D printing community have spent countless hours advancing their 3D printer designs and figuring out how to maximize the quality of the prints while minimizing the overall cost of the machine. The "Aluminum Mendel" found on Thingiverse.com is a great example of these do-it-yourself (DIY) 3D printers as shown in Figure 3.

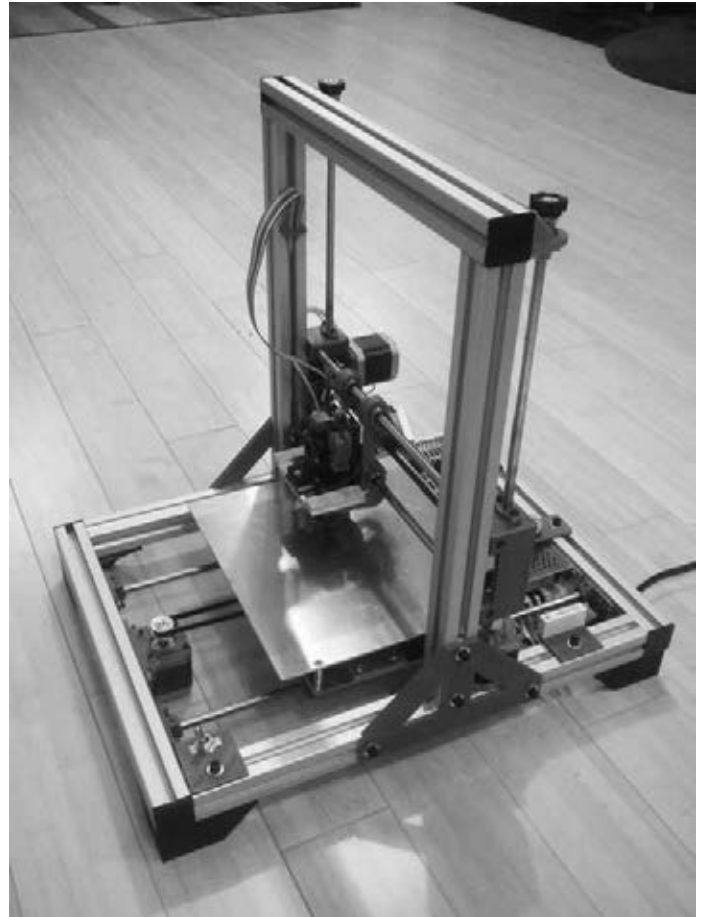
The plastic STL part files, a bill of materials, and exploded drawings are available online. Educators can communicate with other individuals who have built the same printer to discuss difficulties they encountered while constructing the 3D printer. These projects require ordering a variety of components from several different websites, around 60-70 hours of printing time to make all the plastic parts, and up to 50 hours of assembly depending on the builder's skill level. Skills required for a project like this include custom metalworking, basic knowledge of motor and pulley systems, and advanced electrical schematic interpretation. There is a great deal of intricate wiring that goes into building a 3D printer, but the schematics available with the components help with step-by-step instructions. After assembling a DIY 3D printer of this quality, one can appreciate the amount of detail that has been added to every component. These 3D printers have the capability of being fine tuned to ensure the highest quality printed parts. Avid builders can experiment with improvements on existing components and add customized features to satisfy various 3D printing needs.

## CONCLUSION

3D printing has the ability to revolutionize technology and engineering education. The concept of “think globally, produce locally” has never been more apparent. 3D printing technology has made significant advancements over the past few years and now is more affordable than ever. The versatility of this machine provides technology and engineering educators with the ability to engage their students with many different STEM-based activities that help to meet educational standards. Educators who embrace 3D printers and incorporate the machines into their classroom activities may make a significant impact in their students' lives. The power that this technology holds is only limited by one's imagination. Having the ability to share ideas and learning activities will expand avenues in how educators present technical concepts to their students. There is something truly amazing about having an affordable machine that can turn an idea into reality in a matter of hours!

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**Figure 3.** The Aluminum Mendel. ([www.thingiverse.com/thing:16076](http://www.thingiverse.com/thing:16076))



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