FORMLABS GUIDE FOR EDUCATORS

3D Printing Lesson Plan Bundle for STEAM Education

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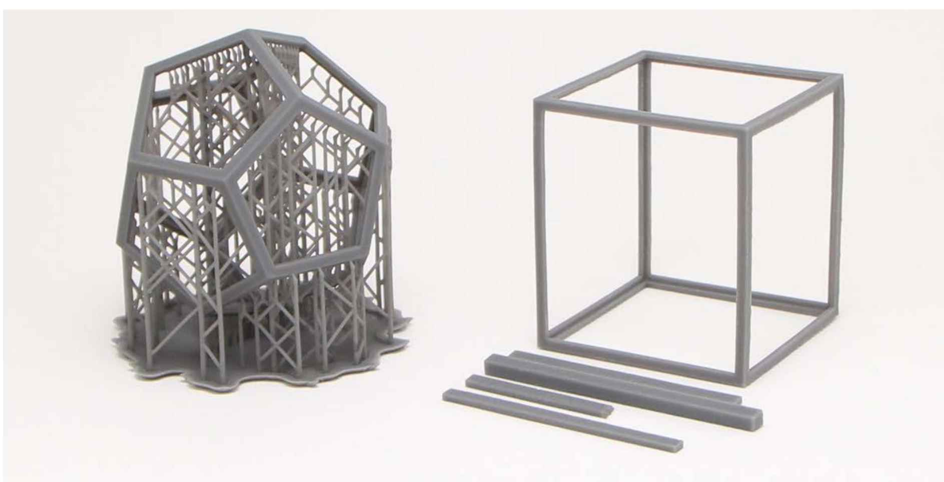
3D Printing for STEAM Education

Both higher education institutions and K-12 schools are adopting 3D printing as a tool to enhance learning. For many teachers, 3D printing is still a new technology, and it can be a challenge to figure out how to integrate it into curriculum. 3D printers are learning tools, much like a calculator and a ruler. Rather than changing existing classroom material to focus on 3D printing, teachers are using 3D printers as a tool to enhance their class.

At Formlabs, we believe that sharing curriculum and resources is one of the best ways to help fellow educators understand how to integrate 3D printing into existing or new lessons. We reached out to our educator ambassadors and asked them to submit lesson plans that included aspects of 3D design and 3D printing. You can find all of our ambassador's lesson plans **on our education resources page.**



This model is from the **Dodecahedron Lesson Plan**, submitted by the Science Visualization Initiative.

This guide includes two sample lesson plans from top educators, a case study with a Career and Technical Education (CTE) educator, and an overview of different 3D printing technologies. Use this guide as a resource to gain insights and ideas for how to create new or existing lesson plans that integrate 3D printing and design into your classroom.

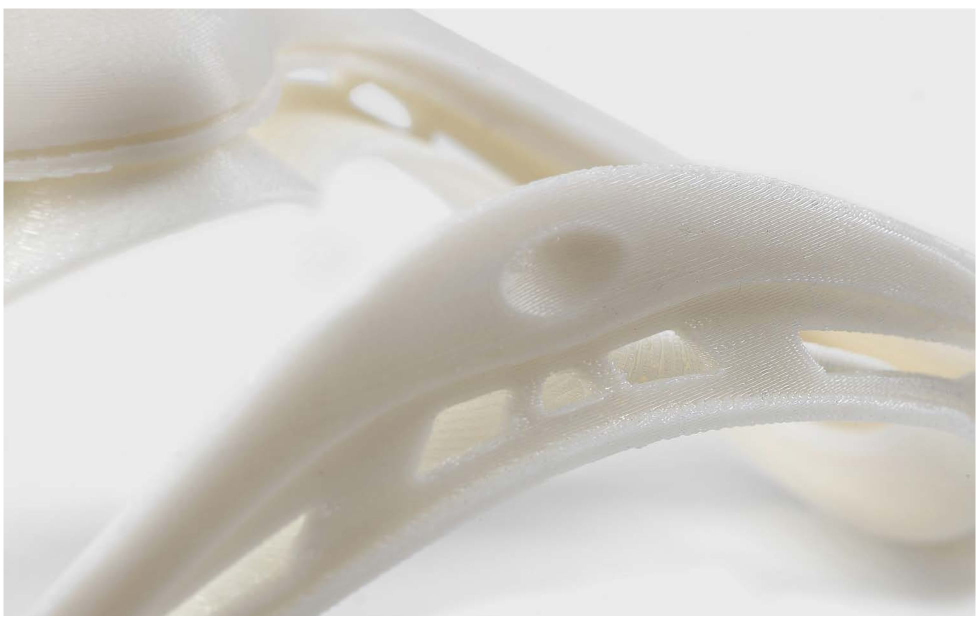
Take me to more lesson plans

3D Printing Technologies Overview

Each 3D printing technology has its own strengths, weaknesses, and requirements, and is suitable for different applications and businesses. Here is an overview of how each technology works:

FUSED DEPOSITION MODELLING (FDM)

Fused Deposition Modeling is the most widely used form of 3D printing at the consumer level, fueled by the emergence of hobbyist 3D printers. FDM 3D printers build parts by melting and extruding thermoplastic filament, which a print nozzle deposits layer by layer in the build area. FDM works with a range of standard thermoplastics, such as ABS, PLA, and their various blends. The technique is well-suited for basic proof-of-concept models, as well as quick and low-cost prototyping of simple parts, such as parts that might typically be machined.



FDM parts tend to have visible layer lines and might show inaccuracies around complex features. This example was printed on a Stratasys uPrint industrial FDM 3D printer with soluble supports (machine starting at $15,900).

FDM has the lowest resolution and accuracy when compared to SLA or SLS and is not the best option for printing complex designs or parts with intricate features. Higher-quality finishes may be obtained through chemical and mechanical polishing processes. Industrial FDM 3D printers use soluble supports to mitigate some of these issues and offer a wider range of engineering thermoplastics, but they also come at a steep price.

STEREOLITHOGRAPHY (SLA)

Stereolithography was the world's first 3D printing technology, invented in the 1980s, and is still one of the most popular technologies for professionals. SLA uses a laser to cure liquid resin into hardened plastic in a process called photopolymerization.

SLA parts have the **highest resolution** and accuracy, the clearest details, and the smoothest surface finish of all plastic 3D printing technologies, but the main benefit of SLA lies in its versatility. Material manufacturers have created innovative SLA resin formulations with a wide range of optical, mechanical, and thermal properties to match those of standard, engineering, and industrial thermoplastics.

SLA parts have sharp edges, a smooth surface finish, and minimal visible layer lines. This example part was printed on a **Formlabs Form 2 desktop SLA 3D printer** (machine starting at $3,499).

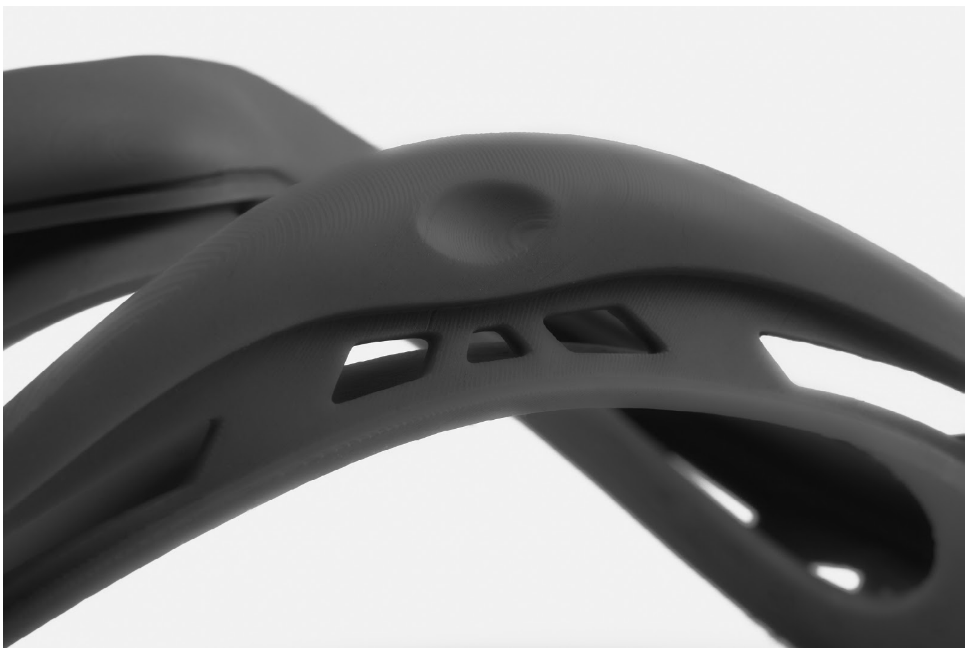
SLA is a great option for highly detailed prototypes requiring tight tolerances and smooth surfaces, such as molds, patterns, and functional parts. SLA is widely used in a range of industries from engineering and product design to manufacturing, dentistry, jewelry, model making, and education.

Order a Sample Part

SELECTIVE LASER SINTERING (SLS)

Selective laser sintering is the most common additive manufacturing technology for industrial applications.

SLS 3D printers use a high-powered laser to fuse small particles of polymer powder. The unfused powder supports the part during printing and eliminates the need for dedicated support structures. This makes SLS ideal for complex geometries, including interior features, undercuts, thin walls, and negative features. Parts produced with SLS printing have excellent mechanical characteristics, with strength resembling that of injection-molded parts.



SLS parts have a slightly rough surface finish, but almost no visible layer lines. This example part was printed on a **Formlabs Fuse 1 benchtop SLS 3D printer** (machine starting at $9,999).

The most common material for selective laser sintering is nylon, a popular engineering thermoplastic with excellent mechanical properties. Nylon is lightweight, strong, and flexible, as well as stable against impact, chemicals, heat, UV light, water, and dirt.

The combination of low cost per part, high productivity, and established materials make SLS a popular choice among engineers for functional prototyping, and a cost-effective alternative to injection molding for limited-run or bridge manufacturing.

COMPARE FDM, SLA, AND SLS TECHNOLOGIES

Each 3D printing technology has its own strengths, weaknesses, and requirements, and is suitable for different applications and businesses. The following table summarizes some key characteristics and considerations.

The following table summarizes some key characteristics and considerations of FDM, SLA, and SLS 3D printers.

	Fused Deposition Modelling (FDM)	**Stereolithography (SLA)**	**Selective Laser Sintering (SLS)**
Resolution	●●○○○	●●●●●	●●●●○
Accuracy	●●●●○	●●●●●	●●●●●
Surface Finish	●●○○○	●●●●●	●●●●○
Throughput	●●●●○	●●●●○	●●●●●
Complex Designs	●●●○○	●●●●○	●●●●●
Ease of Use	●●●●●	●●●●●	●●●●○
Pros	Fast Low-cost consumer machines and materials	Great value High accuracy Smooth surface finish Range of functional applications	Strong functional parts Design freedom No need for support structures
Cons	Low accuracy Low details Limited design compatibility	Average build volume Sensitive to long exposure to UV light	Rough surface finish Limited material options

Meet a Fab Lab at the Forefront of Advanced Manufacturing Education

Formlabs is trusted by the top educators in the US; 46 of the 50 top universities in the US are powered by Formlabs printers. Read on to find out how one teacher, Jerry Shaw, is using 3D Printing in his CTE (Career and Technical Education) program and Fablab.

At Somerville High School's new fab lab, students learn to use advanced manufacturing equipment, from CNC mills to 3D printers.

Why is it important to bring advanced engineering and manufacturing coursework into schools?

One of the things that's missing in a lot of high schools is that idea of actually thinking through a project from beginning to end. I used to teach a physics class and an engineering class at the same time. Students in the physics class would get bored with the labs, whereas in the engineering class, we'd be covering similar concepts and yet they'd love working on it. Later, I realized that it was the difference between labs and projects: labs have a prescriptive step-by-step process that you can't deviate from, whereas with projects, the kids have their own creative input–something to hold on to that is theirs. Having that excitement around engineering and creating helps them better understand the creative process.

Plus, 3D printers and laser engravers are things that many kids have never seen before. It's easy for them to initially get excited, but then I show them a video of how they're actually being used in industry; that you can actually 3D print prototypes, biomedical devices, organs, even food, and they're hooked.

Manufacturing today looks much different than it did 10 years ago. Schools and universities across the globe are teaching students to use modern technology and processes. Pictured here, Somervillle High School's machine shop.

Beyond that, a lot of traditional jobs have been lost to automated computer-based jobs. Part of the issue is that we don't have people who know how to operate these newer machines; there's a huge demand for those skills. Before we built Fabville, a lot of students were skilled in making things with the older equipment, but not in the new ways things are being manufactured, the digital fabrication side of using 3D modeling and CAD. That's what's being tied in now. Most of my current students have already been offered jobs. I have employers asking me all the time if I have anyone who knows how to run CNCs or digital 3D modeling systems.

What's different about Somerville's CTE model, and how do you see it changing?

Half of my students are going to college and half into the workforce. The stigma that used to exist around vocational programs has gone away, especially in Massachusetts. In the early 90s, the state put a giant emphasis on vo-tech education, to bring it up to high standards and implement more academic rigor.

I went to college for engineering and was never on a vocational track. I didn't know what an engineer was when I graduated high school because those opportunities weren't there. There are so many people in engineering or in design that don't know how to work those machines or how to design. They know theoretically, but not physically. I think because that need to understand is at the forefront now a lot of kids aren't seeing CTE programs as a barrier to college; 70 percent of our freshman class is enrolled in CTE.

By their senior year, students enrolled in the advanced manufacturing track of Somerville High School's CTE program know how to use all of the machines.

All freshmen that enroll go through our exploratory program, where each student spends several weeks cycling through all of the CTE programs–from cosmetics to advanced manufacturing. In my shop some seniors help out with teaching the freshman, assisting them in using the 3D printers, etc. We show them specific projects, what the shop is, and what career paths they could choose. In the fourth quarter, freshmen choose three concentrations and are then placed into one program for rest of their four years. Another one of the nice things is that over that time the kids grow a closeness and a community with the teachers and fellow students. It's like being a part of a club in school. There's a lot of pride.

There are a lot of buzzwords for schools bringing new technology into shared spaces–makerspaces, fab labs, innovation centers, etc. Is there a difference?

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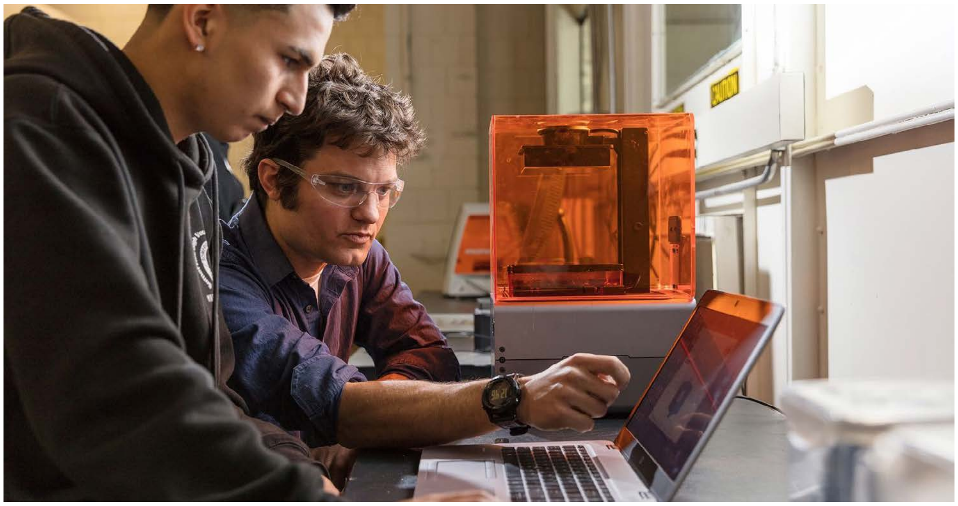
Let's talk more about that example. How does 3D printing specifically fit into your curriculum?

3D printing is faster in many cases, but is generally great for prototyping. We can take a 3D model, send it to the machine, and see how it's going to be built in a more affordable fashion. When it's exactly what we want, we then use stainless steel, which is a little more pricey, and take the time and build with that.

I've also used 3D printing to teach 3D modeling–since 3D printing is fun and engaging it's an incentive for students to learn CAD. Students learn to 3D model using SolidWorks or Inventor, but after a while that can get boring because you're just on the computer, so we create their actual physical part using 3D printing. Then, students use measurement tools to double check and make sure everything printed correctly; learn the quality control aspects of it. At that point we're getting into some of the manufacturing territory.

Beyond that, 3D printing is a basic tool to solve a lot of issues. So you teach how to use it in a structured way with 3D modeling, and then later on it's a tool to use to solve any other problem, much like a saw would be. This helps students to understand how to use technology in context, then, later on if they have their own ideas, they can come back and work on those as well. All of my seniors know how to use all the equipment we have for the most part.



Shaw uses 3D printing as a prototyping tool, and to teach valuable CAD and 3D modeling skills, finding that students are more engaged when they're able to bring their designs to life.

In addition to regular curriculum, the way we use Fabville is that we'll have jobs come in—here's the problem, you've gotta solve it. For example, a knob to a steamer in the cosmetology shop broke and snapped off. One of my students went up there and measured everything out, designed a 3D model for the knob, and knew the knob had to be very precise in order to fit into the space in the machine, so he chose to print it with our Formlabs 3D printer.

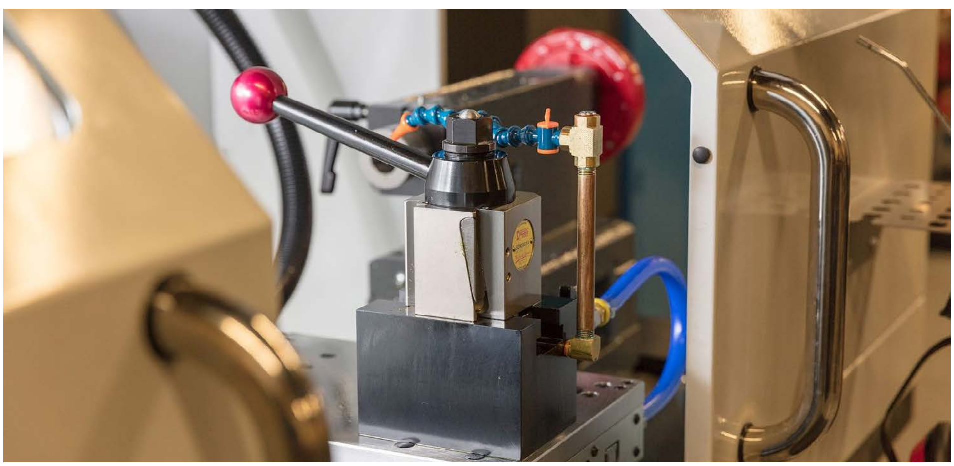
Learn more about how educators are using 3D printers in the classroom.

Students in advanced manufacturing perform jobs for other school departments and CTE tracks, such as creating the placards pictured above for the culinary arts program.

What do you see as some of the barriers for educators adopting new technology, and how do you find resources or inspiration?

While I do have engineering experience, I don't have experience in all engineering or all 3D printing. I didn't know anything about 3D printing until a few years ago when it got kind of thrown at me.

One of the resources I use is teachengineering.org, a website created by a bunch of engineering educators that teamed together realizing there's not many resources to share what we're doing. Another way is just collaborating with engineering educators in general, talking to people in the industry to see what's being used out there. Even as simple as going to the Museum of Science, walking around, seeing the ideas they have, and thinking, "how can I integrate that into my classroom?" Also just having the curriculum ideas and the lessons to get started. A lot of people don't have experience in designing or creating with these things, so having lesson plans out there that guide them in direction or help them know what's important to look for can be a big help. Download Somerville High School's lesson plan "Principles of 3D Modeling and 3D Printing" and sign up for our newsletter for updates as our lesson plan library grows.



After school, Fabville and the machine shop host retraining programs in partnership with a local manufacturing consortium.

What other kinds of programs does Fabville support? How does the space fit into the community?

Right now we're in our first year, so we're ramping up to get all of these programs set up. The idea is that people who don't necessarily feel comfortable creating things or working on machines, but want to learn how, can come here and gain that knowledge and background. People who are out of work can come here learn skills like 3D modeling that will help them get back into the workforce. Down here in the machine shop we actually have a collaboration with a local manufacturing consortium that's putting people who have been laid off through machining classes, so they can get some of the jobs out there that employers really need filled.

As far as Somerville itself, hopefully the goal down the line is that more and more people looking to create their own businesses, even some of our students with entrepreneurial ideas, can get started here. Our role is not to augment or replace what other community fabrication centers or makerspaces are doing, but to create a launch pad for people who aren't necessarily as comfortable going to a space where there are a lot of people working; it's a safe environment to slowly get to know how to use the machines, then step up to another space or go straight to creating a business.

What's next for Fabville?

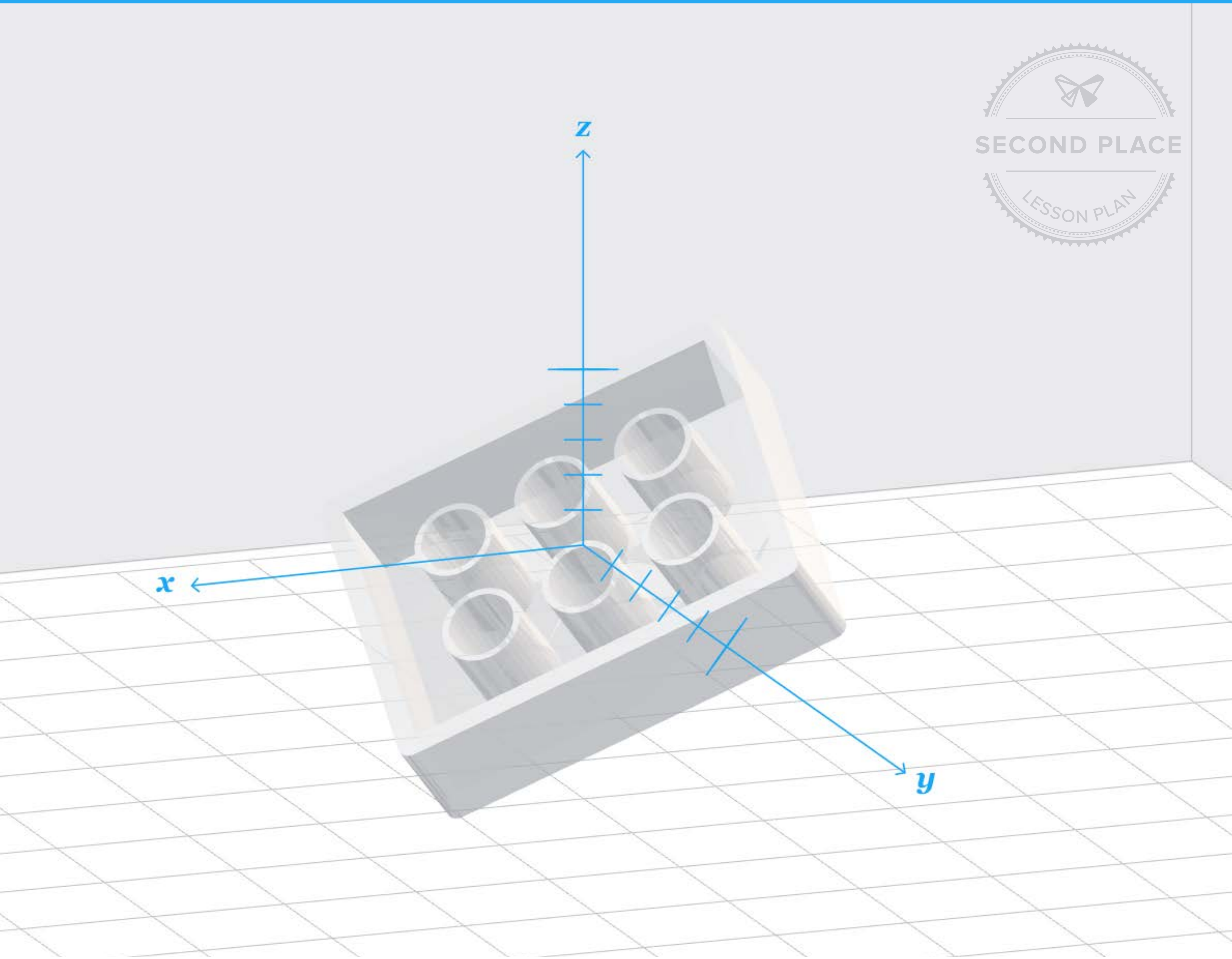
One of the greatest aspects of the future is our new high school that just got approved. In the new setup, the machine shop and fab lab will be next to each other, we'll have a few machines that will make things easier, such as electronic textiles, and all of the CTE departments will also be interspersed throughout the high school itself.

We'll be also be looking to implement some robotics and mechatronics programming, and starting to teach students how to design robots and implement them into manufacturing processes.

Learn More on our Education Resources Page

Lesson Plans

The following lesson plans were written, used, and classroom-tested by accredited educators across North America. Take these lessons and use them as they are, or use them as inspiration to integrate 3D printing into one of your own lesson plans.



FORMLABS LESSON PLAN

Principles of 3D Modeling and 3D Printing

A launch pad into creating objects using computer-aided design (CAD) and 3D printing, with lessons in design for manufacturing.

Adapted by Formlabs, original submission by Jeremy Shaw of Somerville High School.

formlabs

Formlabs' Innovate & Educate Challenge invited educators across the country to develop and share lesson plans that encourage creative thinking and hands-on learning through 3D printing. Thanks to those who submitted, we're able to share free resources with a wider learning community dedicated to inspiring students with rich, immersive experiences.

Learn more about our growing library of lesson plans.

Missed the challenge but have an innovative lesson plan you'd like to share? Find more information at **formlabs.com/innovate-and-educate-challenge**

Lesson plan tested and submitted by:

EDUCATOR
Jeremy Shaw

ORGANIZATION
Somerville High School

LOCATION
Somerville, Massachusetts, USA

CONTACT
jshaw@k12.somerville.ma.us

SUMMARY

Principles of 3D Modeling and 3D Printing creates ties between the familiar Cartesian coordinate system and modeling objects in three-dimensions with computer-based software. The activities will challenge how students think about everyday objects by distilling them first into planar projections. Students will experience a complete design cycle, from brainstorming and taking measurements, to modeling, 3D printing, and analyzing their products. This lesson will equip students with hands-on foundations of CAD, 3D printing, and design for manufacturing.

OBJECTIVES

- Learn about mathematical frameworks for modeling objects in two dimensions and in three dimensions
- Learn how to model objects using CAD
- Learn about design for manufacturing

SUGGESTED AUDIENCE

8^{th} – 12^{th} grade students or beginner 3D designers

SUBJECT & INDUSTRY LINKS

Applicable Subjects

mathematics
engineering
product design
manufacturing

Applicable Industries

research & education
engineering & product design
model making & entertainment
manufacturing

TOOLS & MATERIALS

TO SHARE

Form 2 & Resin | PreForm Software | .STL File * | Whiteboard & Markers

PER STUDENT / GROUP

Computer | Paper | Pencil | Ruler | Onshape or other 3D Modeling (CAD) Software

LESSON OVERVIEW

5 min	**Do Now**	**Sphere** Students will make a prediction about how 3D modeling software is used to create a sphere.
40 min	**Foundation**	**Framing 2D and 3D Space** Students are introduced to 2D vectors and 3D vectors as a means of understanding the mathematical roots of 3D modeling software.
3 hr	**Exploration**	**CAD Basics** Students will be introduced to basic concepts of translating 2D sketches into 3D models and will learn the fundamentals of a CAD software. **Modeling using CAD** Students will create two models (a six-sided die and a bowling pin) using dimensions they will find on their own. They will generate assemblies if time allows. **Lego Challenge** Students will be introduced to manufacturing using 3D printers and will design, model, and print a custom part that connects to a standard Lego piece.
30 min	**Retrospective**	**Precision** The class will inspect their printed pieces and analyze dimensional differences between their designs and their end products.
5 min	**Closing**	**Looking Forward** The class will discuss the manufacturing, cost, and other implications of precision machining and the importance of designing with machine-specific tolerances in mind.

* Download the .STL and .FORM files at: **formlabs.com/esson-plan-principles-of-3d-modeling-and-3d-printing/**

ACTIVITY ONE

5 min **Do Now**

1. Ask students to write down their prediction of how computer-aided design (CAD) software is used to model a sphere.

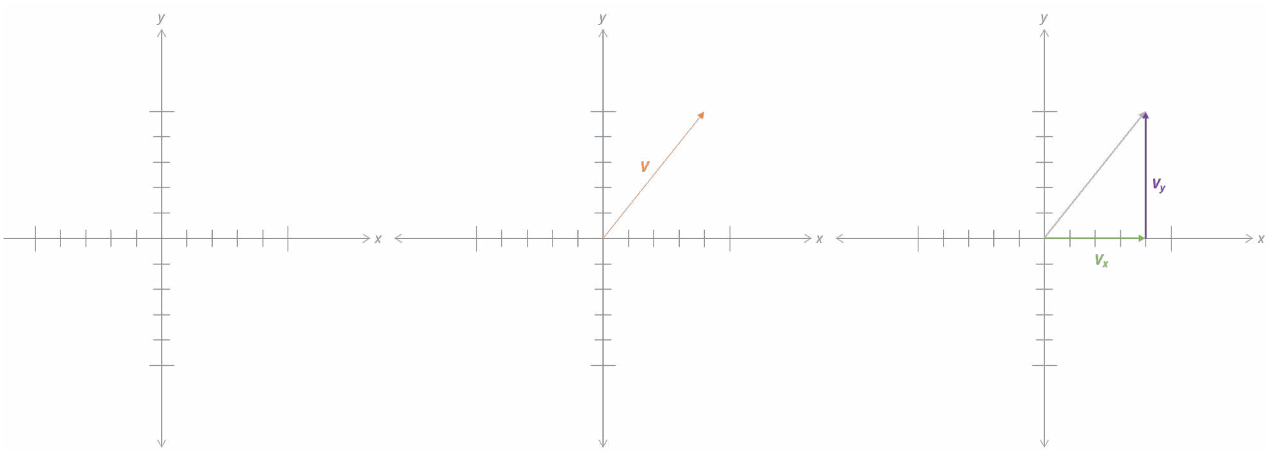
ACTIVITY TWO

5 min **Foundation**

1. Introduce students to the relevance of 3D modeling in our day-to-day lives (see below).

2. Provide students with background information on vectors, planes, and the Cartesian coordinate system, as they relate to 3D modeling with CAD software (see below).

3. **Two-Dimensional Cartesian System:** On the board, draw an X, Y coordinate plane with scale marks. Draw a vector (V = 4,5) in Quadrant I and break the vector into its X (V_x = 4,0) and Y (V_y = 0,5) components, where $V_x + V_y = V$.

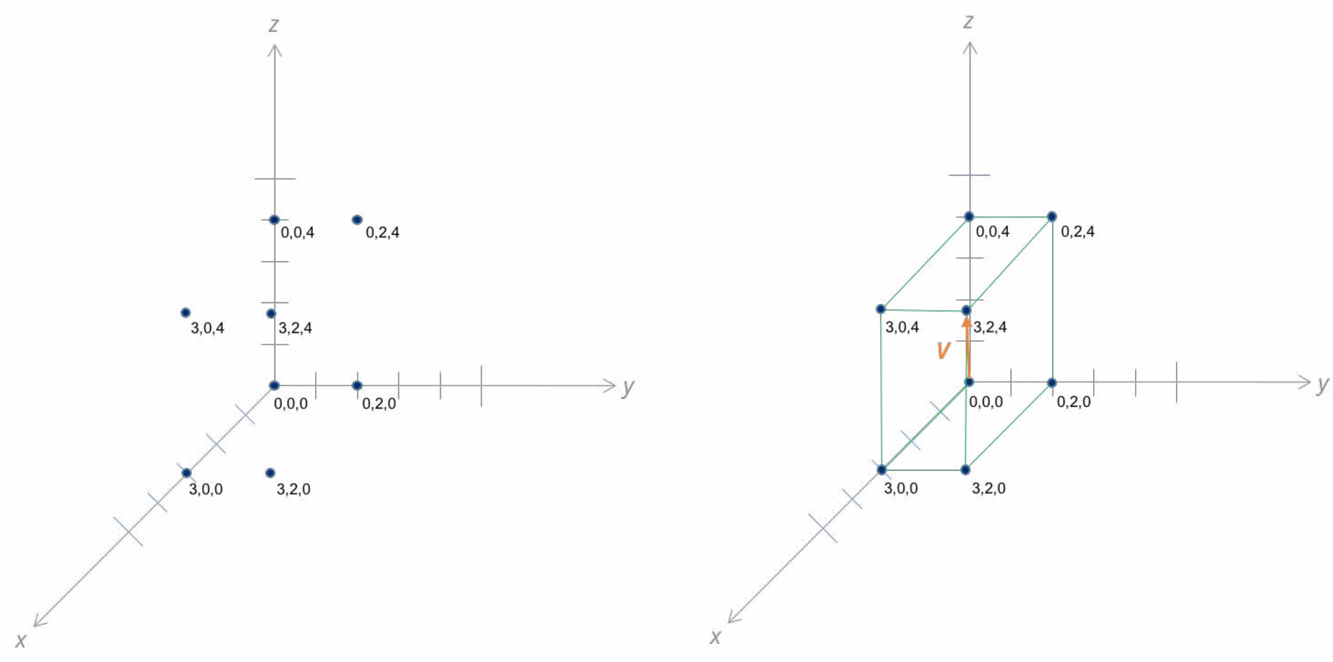


4. Draw three additional vectors (arrows) on the board and ask students to decompose them into their component vectors.

> **Tip:** Each vector is the diagonal of a rectangle. Understanding how to mathematically determine the vertices of the rectangle will greatly help with drawing vectors in a three-dimensional Cartesian system.

	VERTEX	X	Y	DESCRIPTION
	1	0	0	origin
V = 4, 5	2	4	5	vector
	3	4	0	x-component
	4	0	5	y-component

5. **Three-Dimensional Cartesian System:** On the board, draw an X, Y, Z coordinate plane with scale marks. Walk through the steps of drawing a vector (V = 3, 2, 4) by way of a rectangular prism (see above Tip).



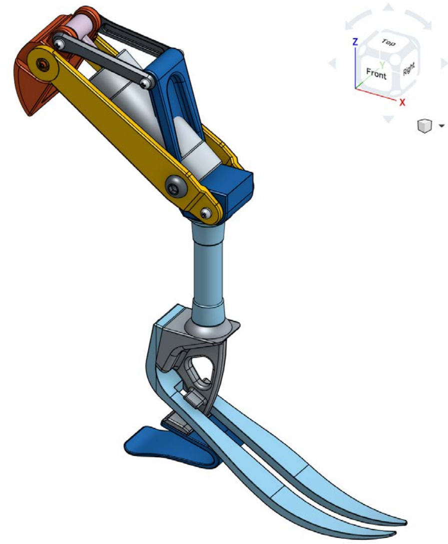
	VERTEX	X	Y	Z	DESCRIPTION
	1	0	0	0	origin
	2	3	2	4	vector
	3	3	0	0	x-component
V = 3, 2, 4	4	0	2	0	y-component
	5	0	0	4	z-component
	6	3	2	0	xy-vertex
	7	0	2	4	yz-vertex
	8	3	0	4	xz-vertex

6. Provide students with several (x,y,z) vector coordinates and instruct them to practice drawing the vectors (V, V_x, V_y, and V_z) using the Cartesian coordinate system as demonstrated. e.g. (10, 10, 10), (5, 10, -5), (1, 3, 8).

BACKGROUND

3D modeling is a visualization and analytical tool with many purposes and benefits. Modeling enables ideas to be communicated, structural feasibility of designs to be tested via simulations, and parts and assemblies to be iteratively improved prior to fabrication. For example, in the matter of days, a part can be modeled with computer-aided design (CAD) software, its physical properties can be analyzed under realistic forces, and engineers can update the model as needed. Modeling saves companies valuable time, money, and resources and is an integrated part of automotive, defense, engineering, fashion, architecture, energy, game design, entertainment, and medical industries, among others.

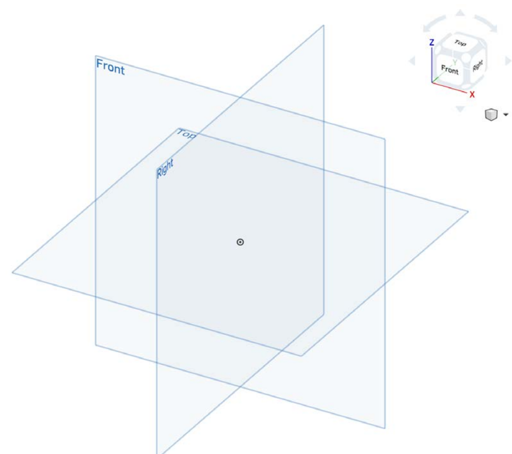
CAD model of a prosthetic leg. »



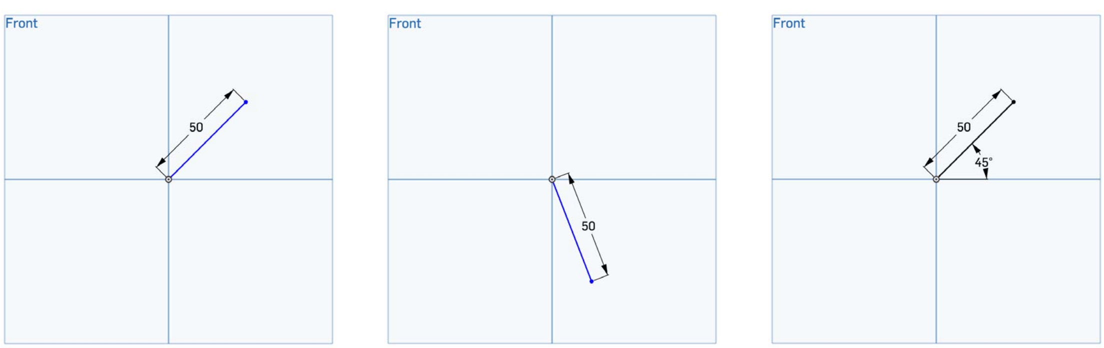
Vectors and planes allow 2D computers to visually represent 3D environments. A vector, often represented by an arrow, is a geometric object with two properties: length and direction. A plane is a two-dimensional surface that extends infinitely far.

Consider a **Cartesian coordinate system** for a three-dimensional space. The coordinate system consists of three intersecting, pair-wise perpendicular planes. The intersections of these planes become the axes for each direction: X, Y, and Z. CAD often displays the Cartesian planes as reference guides.

The starting point in **CAD** is an empty work space, which in the case of Onshape, displays the three-dimensional Cartesian planes.



Consider how you would draw the first line of a part in a CAD program, on the Front Plane and starting at the origin. It is not enough to simply draw a line and move on. You must tell the computer the length of this line (e.g. 50 mm). The 50 mm line starting at the origin can still be moved, because it is not fully defined. It needs a direction (or an angle). Only when this line has a set length and direction, when it is a vector, will it be useful in a 3D model.



ACTIVITY THREE

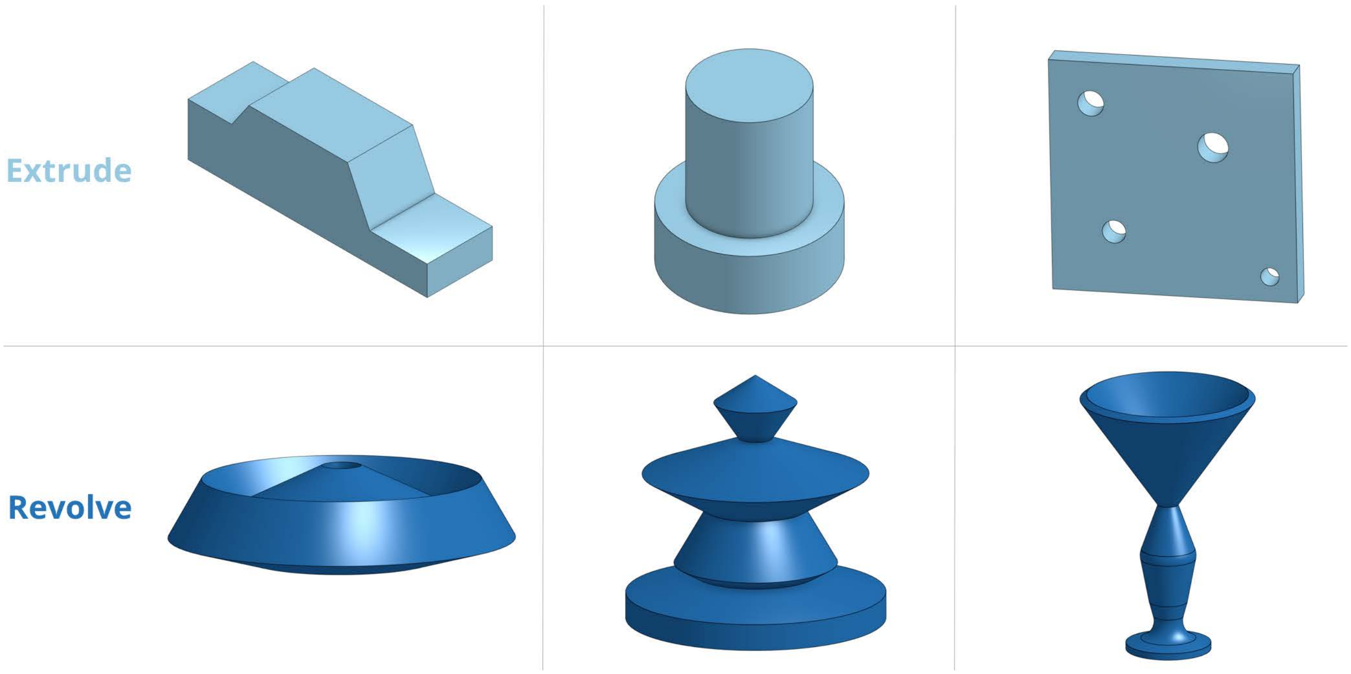
3 hr **Exploration**

1. Explain the principles of geometric and solid modeling to students.

2. Demonstrating with a CAD program, teach students about the process of converting 2D sketches into 3D objects (extrude, revolve).

   Optional: Draw a simple shape on the board (e.g. circle) and ask students what could be done with the circle to turn it into different 3D shapes. Similarly, make a list of common 3D shapes (e.g. sphere, disc, cone, cube, dome) on the board and ask students how 2D shapes could be used to model each.

3. Show students several images of CAD parts that were extruded and several that were revolved, and ask students to draw the foundational sketch for each.



4. Discuss additional tools commonly available in CAD programs (e.g. sweep, loft, fillet, and chamfer, etc.), as well as the power of rendering.

5. Introduce students to the command structure of the CAD program.

6.  Challenge students to create a model of a **six-sided die** (using either dots or numbers).

7. Challenge students to create a model of a bowling pin (candlepin or ten-pin) with the red stripes!

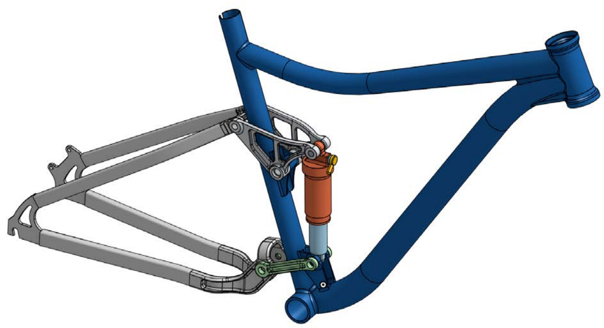
   Optional: Ask students to also model a bowling ball and bowling lane, and to assemble bowling pins and a bowling ball in a lane.

BACKGROUND

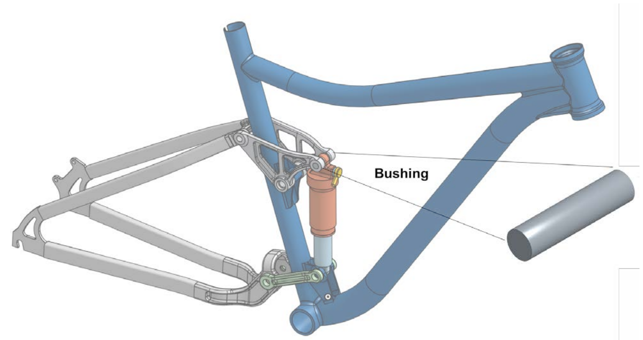
3D modeling is founded on principles of both **geometric** and **solid modeling**. Geometric modeling involves representing objects by equations, whereas solid modeling involves defining values (lengths, angles, and other spatial relationships) within an object.

For example, a company has created a model for a bike. This geometric model is governed by a set of equations, so that the frame can be scaled based on the height of different riders. Once rider heights are known, the geometric model (equation-based) can be converted into a solid model (fully defined).

2D before 3D The 3D modeling design process begins with a 2D **sketch**. Consider a cylindrical part, a bushing, within the bike frame model.



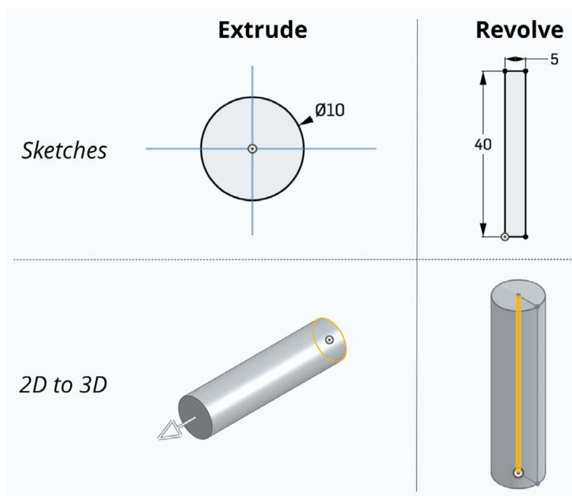
CAD model of a bike frame.



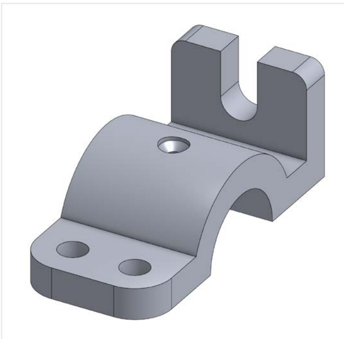
CAD model of a bike frame, with a call-out to a cylindrical part called a 'bushing'.

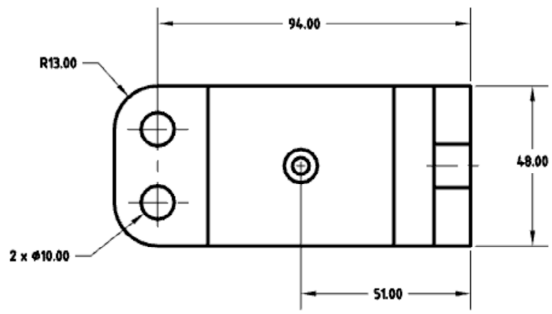
There are two basic ways this bushing can be modeled. It can **extruded** from a circle or **revolved** from a rectangle. Extrusion can be thought of as "pulling" or "stretching" a shape in a specified direction; revolving is the process of rotating a sketch around an axis.

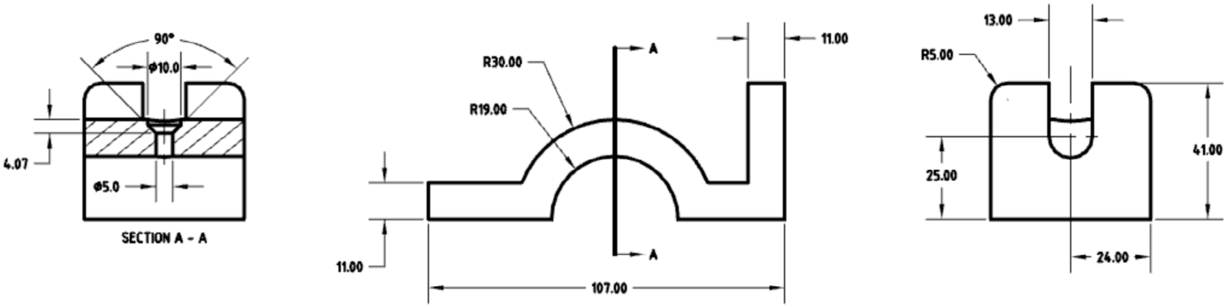
Explore additional tools, such as **sweep**, **loft**, **fillet, and chamfer**, and **more**.

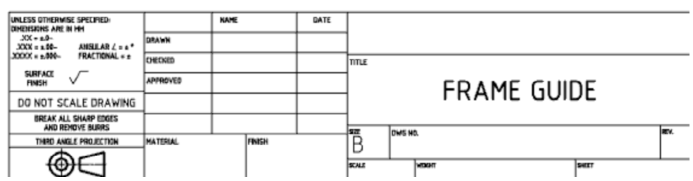


File Types There are several part files that are associated with CAD: part files, assembly files, drawing files, and files that can be read by 3D printers (.STL files). A drawing is based on a part and depicts 2D views and dimensions of the part. These drawings can be passed onto machinists, for instance, who use the drawing as a guide for what to make. Parts can be combined into groups of parts, or assemblies.









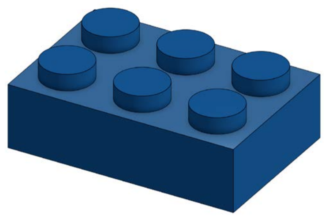
An example of a drawing generated in a CAD program, Onshape.

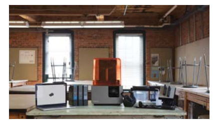
Finishing Touches In addition to modeling the shape of objects, the material appearance of objects may also be customized. The model of a glass tabletop can be edited to look like a glass tabletop. A rendering of the glass desk in an office setting, with the appearance of natural light streaming through the windows, can be generated.

INSTRUCTIONS

1. **3D Printing** Explain to students how stereolithography (SLA) printing works, alongside a live demo.

2. **Challenge** Provide each student with several standard Lego pieces. Introduce students to the next activity: design, 3D model, and 3D print a custom Lego piece. This can be furniture for figurines, an animal, or a specialized building part, for example.





3. **Constraints** Outline the design criteria:
   - Custom piece must mate with a Lego piece
   - Part must fit inside a 40 mm cube
   - CAD file must be in metric units
   - Minimum part thickness = 2 mm
   - Add additional criteria as appropriate for your classroom.

4. **Iteration One** Allow students time to sketch several design ideas.

5. **Design for Printing** Explain additional nuances of designing for a 3D printer. Some examples include: optimal part orientation, tolerance considerations, and the role of support material.

6. **Feedback** Provide students with design feedback, particularly if the design could be adapted to be more 3D printable.

7. **Iteration Two** Ask students to modify their top-choice design based on feedback.

8. **Lego Drawing** Have students sketch an isometric view of the Lego piece that their custom part will mate with. Ask students to leave one blank per dimension.

9. **Dimensions** Provide students with measuring tools (rulers, calipers, micrometers) for completing their Lego drawings, with all dimensions.

10. **CAD** Assist students as they make a 3D model of their custom Lego parts.

11. **PreForm** Help students prepare their .STL files in PreForm, for optimal printing.

12. **Print Parts** Guide students through 3D printing and post-processing their parts.

ACTIVITY FOUR

30 min **Retrospective**

1. **Measurements** Have students measure all dimensions of their printed parts, using the appropriate measuring tools, and create a labeled drawing of their part.

2. **Analysis** It is expected that not all designed dimensions will align with the actual measurements. Ask students to complete a per-dimension analysis, comparing their design values to their actual values, and to hypothesize reasons for discrepancies.

ACTIVITY FIVE

5 min **Closing**

1. **Retrospective** Ask students to consider the implications of manufacturing precise parts on the machine (3D printer) design, the speed of the print, the cost of the part, and any other relevant factors?

Background

Due to a number of factors (printer, print method, machine cost, machine age) prototyped parts will not exactly match their 3D models. Printer clarity can be discussed in terms of horizontal **resolution** (XY resolution) and vertical resolution (layer thickness). The less movement the printer can make on the X and Y axes, and the smaller the layer thickness, the smoother and more precise the printed surface will be. Note that there are time and cost tradeoffs with higher precision. **SLA** 3D printers can produce high-resolution objects. Their resolution is directly linked to the optical spot size of the laser, which is 140 microns for the Form 2.

A benefit to 3D printing is the ability to **quickly iterate**. Once design-to-actual part differences are determined, the design can be modified to improve the part precision.

Contact Formlabs to learn how desktop SLA can work in your classroom.

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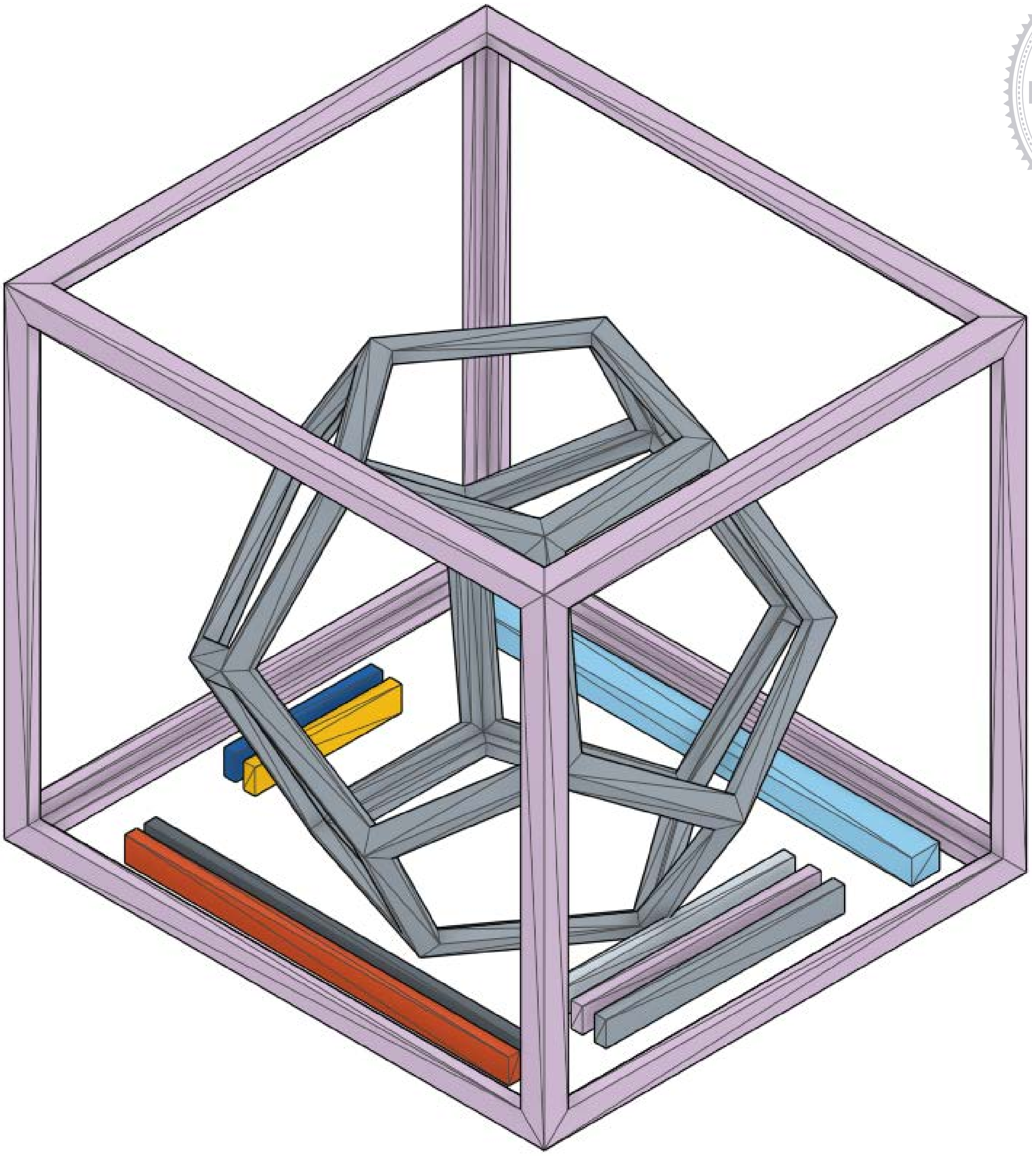
FIRST PLACE
LESSON PLAN



FORMLABS LESSON PLAN

The Dodecahedron

An artistic exploration into links between our 3D world and 2D methods of visualization.

Adapted by Formlabs, original submission by Chris Sloan of Science Visualization.

Formlabs' Innovate & Educate Challenge invited educators across the country to develop and share lesson plans that encourage creative thinking and hands-on learning through 3D printing. Thanks to those who submitted, we're able to share free resources with a wider learning community dedicated to inspiring students with rich, immersive experiences.

Learn more about our growing library of lesson plans.

Missed the challenge but have an innovative lesson plan you'd like to share? Find more information at **formlabs.com/innovate-and-educate-challenge**

Lesson plan tested and submitted by:

EDUCATOR
Chris Sloan

ORGANIZATION
Science Visualization

LOCATION
Cumberland, Maryland, USA

CONTACT
chris.sloan@sciencevisualization.com

SUMMARY

The Dodecahedron makes use of a 3D printed kit to introduce students to hands-on methods of translating three-dimensional objects into two-dimensional space. The lesson draws historical connections to notable mindsets and techniques around orthographic views, linear perspective drawings, dodecahedron geometry, the golden ratio, and the Fibonacci series. Students will journey from pre-Renaissance schools of thought, through how da Vinci's contributions have shaped how we depict our world, to innovations enabled by 3D modeling advancements.

OBJECTIVES

- Learn about translating three-dimensional objects into two dimensions
- Learn about Platonic solids
- Learn about geometric ratios in nature and in design
- Learn about projective geometry

SUGGESTED AUDIENCE

6th – 10th grade students

SUBJECT & INDUSTRY LINKS

Applicable Subjects

mathematics
art
engineering

Applicable Industries

engineering & product design
research & education
model making & entertainment

TOOLS & MATERIALS

TO SHARE

Form 2 & Resin

Tape

Computer

PreForm Software

.STL File *

PER STUDENT / GROUP

3D Printed Dodecahedron Kit

Paper & Acetate

Pencil

Marker

Compass

Ruler

LESSON OVERVIEW

5 min	**Do Now**	**Sketch Challenge** Students will attempt to translate their view of a 3D printed dodecahedron into a paper sketch.
10 min	**Foundation**	**Background** Introduce students to the “rationalization of space” and its connection to many industries, including 3D modeling, animation, architecture, game design, fine arts, and engineering.
30 min	**Exploration**	**Projections** Using a 3D printed Dodecahedron Kit, guide students through drawing a more precise dodecahedron. Use the “projection box” to teach principles of orthographic views as a way of translating three-dimensional space. **Golden Ratio** Walk students through an exploration of the proportions (the Golden Ratio) inherent in a dodecahedron and their link to orthographic views. Lead students in the construction of the Golden Ratio and guide them to create one face of a dodecahedron (a pentagon). **Perspective Drawing** Explain the difference between orthographic projections and perspective drawings. Teach students how to use the Dodecahedron Kit to create a perspective drawing of a dodecahedron.
10 min	**Retrospective**	**Connecting the Dots** The class will share their creations and discuss other approaches for developing orthographic views of other objects.
5 min	**Closing**	**Looking Forward** Discuss the relevance of 3D concepts explored in this lesson, in understanding our world and in sparking innovations across many industries.

* Download the .STL and .FORM files at: **formlabs.com/lesson-plan-dodecahedron**

ACTIVITY ONE

5 min **Do Now**

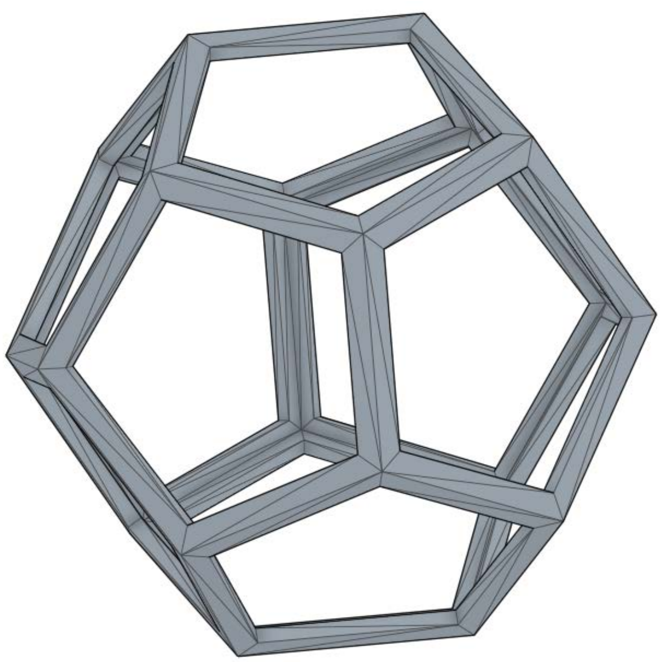
1. Distribute one 3D printed dodecahedron to each student (or student group).
2. Lead an interactive group discussion around the dodecahedron geometry.
3. Explain that the process of drawing objects is translating three-dimensional space into two-dimensional space.
4. Invite students to draw a dodecahedron, using the 3D printed model as a reference.

> Tips: Be encouraging, this is a challenging task. Considering hinting that you will be teaching them 'tricks' for sketching 3D shapes.

5. Give examples of why being able to translate three-dimensional geometries into two dimensions is an important skill.

Dodecahedron Geometry and History
Dodecahedrons are one of five Platonic solids identified 2,400 years ago by the Greek philosopher Plato. They are characterized by have same-length edges and same-shape faces, and are building blocks of our three-dimensional world. Dodecahedrons have 20 equal-length edges and 12 pentagonal faces. Other Platonic solids: cube, tetrahedron, octahedron, icosahedron.

Other Paths to Explore: **Plato**, **Platonic Solids**, **Archimedean Solids**.



ACTIVITY TWO

10 min **Foundation**

1. Review students' sketches and point out that the many edges and faces of a dodecahedron can make the shape confusing to draw.

2. Describe that Pre-Renaissance artists also had difficultly translating three-dimensions into two-dimensional space. Show and discuss **Lorenzetti painting**.

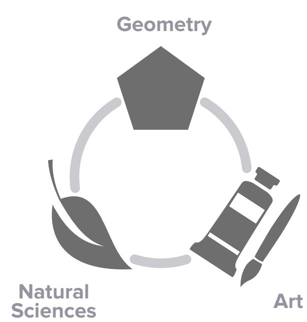
3. Show students two artists' (da Vinci and Durer) drawings of dodecahedrons.

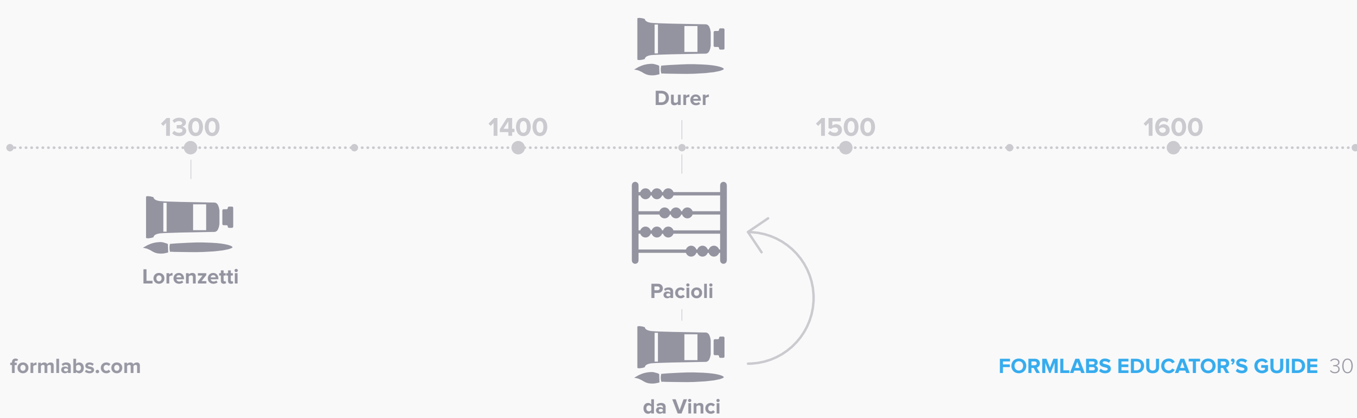
4. Discuss the inter-relatedness of geometry, natural science, and art using the collaboration between Pacioli and da Vinci as an example.

5. Introduce the concept of "rationalization of space" and "projective geometry" in the context of Durer's "perspective machine."

Renaissance Impact
The Renaissance (1300 - 1600) marked a transitional period for the understanding of how to represent 3D objects in 2D. Ambrogio Lorenzetti's painting portrays an unrealistic perspective. Renaissance artists and mathematicians, however, worked together to understand and depict three-dimensional space. These artists included Leonardo da Vinci, who prepared drawings of Platonic solids for the mathematician Luca Pacioli. Similarly, Albrecht Durer was fascinated by the connection between geometry, natural science, and art. Artists like Durer discovered that 3D space can be "projected" onto 2D surfaces in a predictable way. His image of artists using a "perspective machine" illustrates one way to "rationalize space." This was the origin of projective geometry, which is used in many fields of STEAM to this day.

Other Paths to Explore: **Lorenzetti**, **Pacioli**, **da Vinci**, **Durer**.





ACTIVITY THREE

30 min	**Exploration**

1. Help students set up their Kits, with the dodecahedron in the middle and with an acetate sheet ("Picture Plane") taped to a side of the cube ("Projection Box") that is perpendicular to the table. Secure the Projection Box to the table with tape.

2. Instruct students to hold a permanent marker in their dominant hand, and the Eyepoint Stick in their other hand.

3. Have students look at the dodecahedron at eye level, while holding the Eyepoint Stick vertically and halfway between their eyes and the Picture Plane.

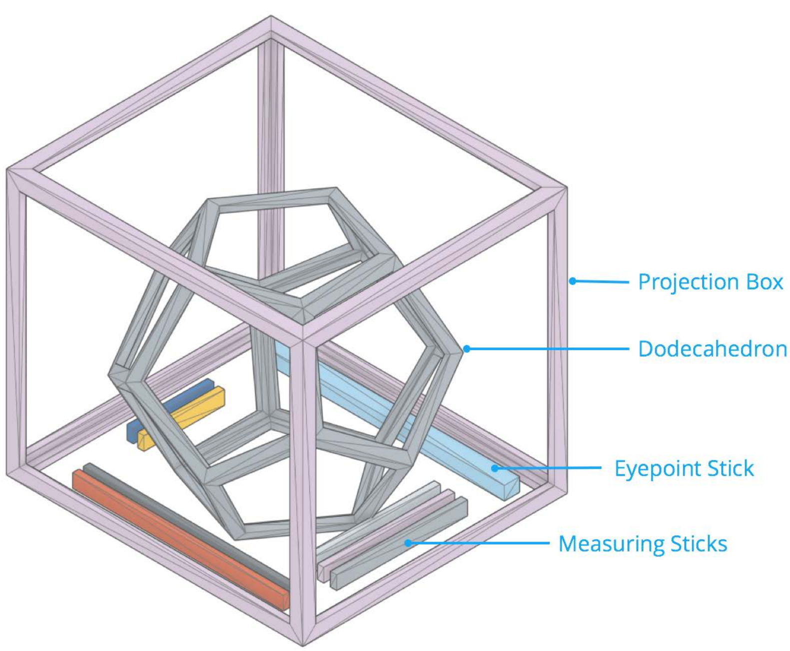
4. Instruct students to close one eye, align the top of the Eyepoint Stick with a vertex of the dodecahedron, and to carefully trace the dodecahedron on the Picture Plane.

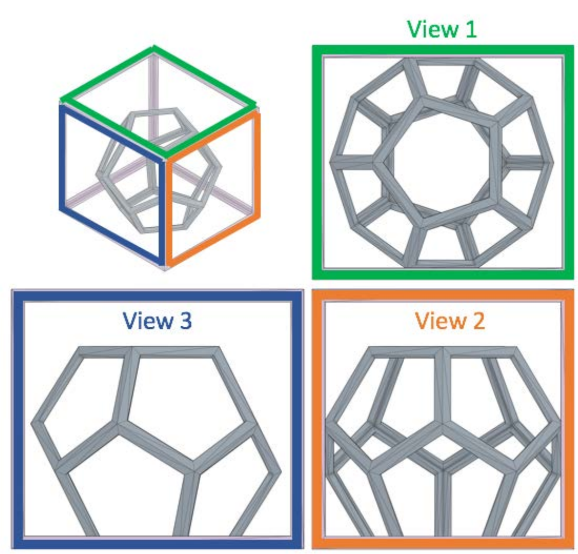
Projective Geometry is the process of translating a three-dimensional object onto a two-dimensional plane.

Orthographic Views are one way that projective geometry is used. The view, or "projection" of the dodecahedron differs depending on the viewing angle. With the dodecahedron inside the Projection Box, there are three distinct **parallel views** - one per dimension. This explains why it takes three **orthographic views** to describe a three-dimensional object.

Linear Perspective is another way that projective geometry is used. This method uses a conical projection, rather than a parallel projection for a 3D-to-2D translation. **Linear perspective** helps artists mimic what the human eye sees.

Renaissance artists used both methods as tools for depicting three-dimensional space in ways that had never been possible before.





ACTIVITY THREE – CONTINUED

30 min **Exploration**

1. Review students' conical projection drawings.
2. Explain to students that complete orthographic views should make it possible to create the object in physical form. Ask students how they would approach creating accurate orthographic views.
3. Explore the relationship between the Fibonacci Sequence and the Golden Ratio with students.
4. Ask students to group their Measuring Sticks by length. There are two small (s), three medium (m), and two large (l) sticks.
5. Use the Measuring Sticks to bring the Fibonacci Sequence and Golden Ratio to life.
   $s + s = m$ is analogous to $1 + 1 = 2$
6. Ask students what the next stick length in the sequence would be.
   $s + m = l$
7. Challenge students to find the Golden Ratio proportions in the dodecahedron.
   s = dodecahedron edge
   m = pentagonal face diagonal
   l = distance between pentagon centers
8. Point out some real-world examples and applications of the Golden Ratio.

Golden Ratio The geometry of pentagons and dodecahedrons is linked to the Golden Ratio, a phenomena that Leonardo's friend, Luca Pacioli, wrote a whole book about. For centuries, artists, mathematicians, and scientists have found this number very interesting, due to its abundant natural presence.

Fibonacci Sequence The Golden Ratio is related to a special sequence of numbers, whereby you start with two numbers and each subsequent number equals the sum of the two previous numbers.

e.g. 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89,...

As the sequence progresses, the result of dividing one number in the sequence by the previous (e.g. 89/55) converges on an irrational number, phi = 1.618..., which is called the golden ratio.

Self-Similarity is a key property of the Golden Ratio. Numbers within the Fibonacci Sequence have this proportional relationship in common.

ACTIVITY THREE – CONTINUED

30 min **Exploration**

1. Challenge students to make two different golden rectangles using the Measuring Sticks. Review relationships from last exercise.

2. Walk students through constructing a golden rectangle using a compass and ruler.

   a. Set compass to radius ‘r’

   b. Draw circle with radius ‘r’

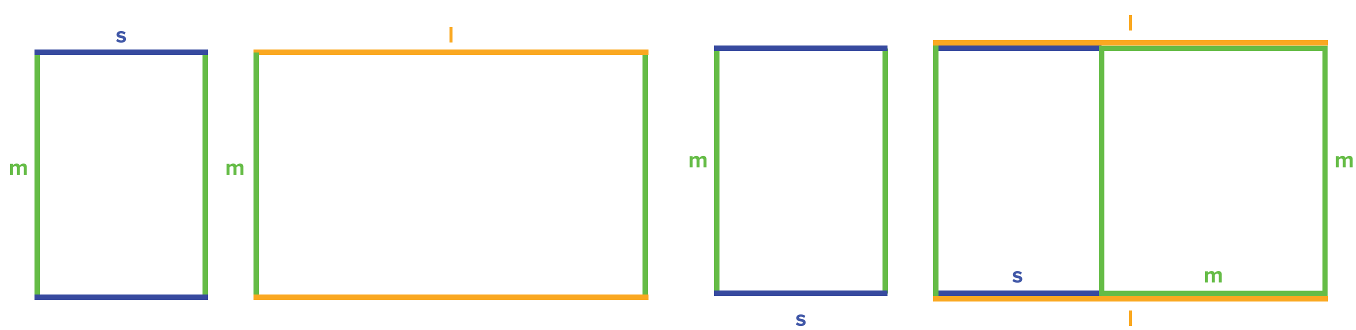
   c. Use ruler to draw square in top right circle quadrant

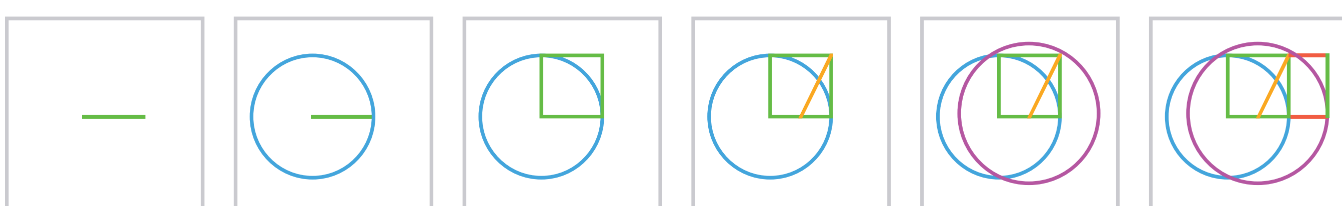
   d. Use ruler to find the midpoint on the bottom side of the square.
   Use ruler to connect this midpoint to the top right corner of the square

   e. Set compass to distance of last drawn line. Draw a new circle, with the origin at the previous midpoint from step ‘d.’

   f. Extend bottom side of square to right side of new circle.
   Then draw the two missing sides of the Golden Rectangle.

Other Paths to Explore: Using compass and ruler to **draw a pentagon**.





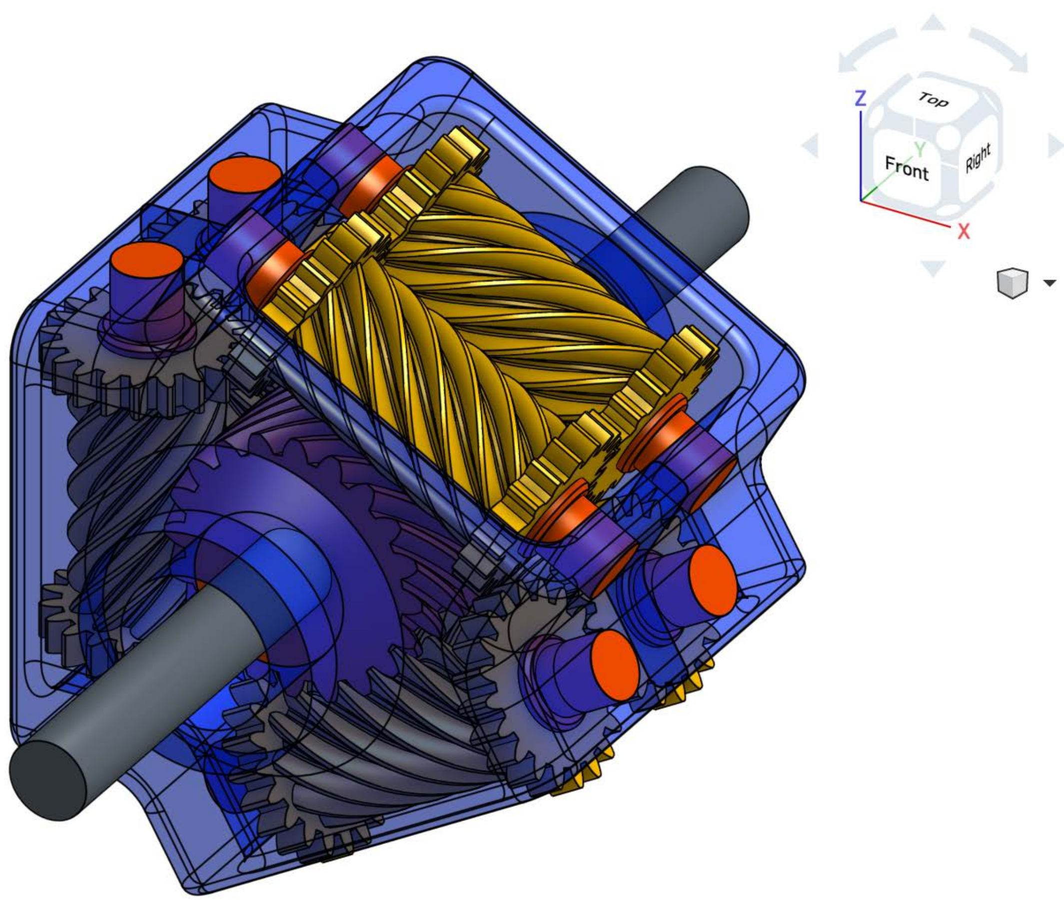
a b c d e f

ACTIVITY THREE – CONTINUED

30 min	**Exploration**

1. Present two orthographic views of the dodecahedron to the students (Side and Top in this example).
2. Explain how two orthographic views can be used to generate a linear perspective of a dodecahedron.

Orthographic View Explained The “Picture Plane Projection” shows the intersection of two views (Top and Side) of the same dodecahedron. The “Picture Plane” receives the conical projection. In this case, there are two picture planes: one from a Side view and one from a Front view. In each of the two views, the points of the dodecahedron are translated onto the Picture Plane Projection. It is the intersection of these views that illuminates a 2D depiction, the “linear perspective drawing,” of the 3D dodecahedron.



ACTIVITY FOUR

10 min	**Retrospective**

1. Review the pathway students followed in understanding what a dodecahedron is and how the Projection Box enabled them to create orthographic views, which then aided in creating a linear perspective drawing.

2. Engage with students about the difficulties around creating a perspective view of **more complicated objects** and landscapes.

3. Discuss ways 3D data are manipulated today: computer-aided-design (CAD), 3D scanning, photogrammetry-based model creation, for instance. Computer and software advancements have greatly enhanced the back-and-forth translation between two-dimensions and three-dimensions.

4. Highlight the next step that 3D printing enables, to bring three-dimensional models to life!

Fun Fact Just as 3D printing software creates 2D stacked slides of 3D parts, 500 years ago, Albrecht Durer also explored this ‘slicing’ concept as a way of creating accurate perspective drawings of humans.

A gear 3D modeled in CAD software.

ACTIVITY FIVE

5 min	CLOSING

1. Lead a brainstorming session with the students, around careers that may require working knowledge of 3D space.

2. Build on students' ideas, by making links to classes that relate to those careers. Some example courses: art, computer science, engineering, geometry, woodworking, machine shop, photography, game design, and more.

We hope this lesson plan was a helpful look at a classroom application for desktop SLA! If you're interested in bringing the plan to your classroom, **download the .STL file** for the Dodecahedron Kit.

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