

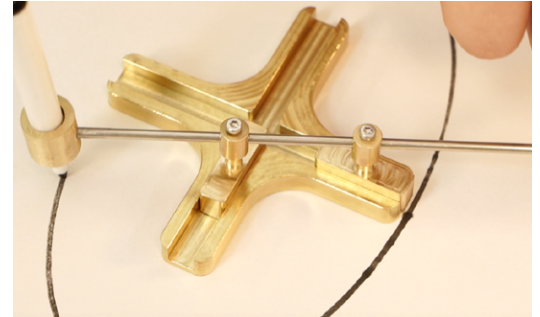
Evolutionary Ellipsographs

Difficulty Level: Intermediate

Duration: Approximately 4 Classes

Lesson Overview:

In the Evolutionary Ellipsographs lesson, students will learn about these mechanical tools as they engage with CAD, CAM, and CNC machining in a design challenge. This activity will allow students to get hands-on with real-world design and manufacturing techniques as they utilize an engineering design process to construct their own prototype solutions. And while this lesson highlights the Trammel of Archimedes specifically, there are also endless ways to adapt and modify this open-ended project.



[Click here](#) to view the overview video for this lesson on the Makera YouTube channel.

Pacing Guide:

Lesson pacing and breakdown may vary based on student prior experience, allotted class time, and available resources.

DAY 1

Begin by introducing the design challenge, expand on the concepts of mechanical tools like the Trammel of Archimedes, and allow students to begin brainstorming stages.

DAY 2

Allow students to transition from the brainstorming stages to the fabrication stages as they develop their designs using CAD software.

DAY 3

Complete CAD designs started previously, introduce subtractive manufacturing and CAM stages (if applicable). Begin to manufacture designs using CNC machines.

DAY 4

Complete CNC machining and transition to the testing and evaluation stages. Allow students to test their prototypes collaboratively before considering ways to improve.

Essential Questions:

As students engage with the topics in this lesson, consider the following essential questions to guide conversations and inquiry:

- Who was Archimedes, and what did he discover?
- What did mechanical tools offer to early engineers?
- Are mechanical tools like the Trammel of Archimedes still used today? What innovations have occurred?
- How are tools like these manufactured?
- What factors and constraints must we consider as we effectively design for subtractive manufacturing?

Learning Objectives:

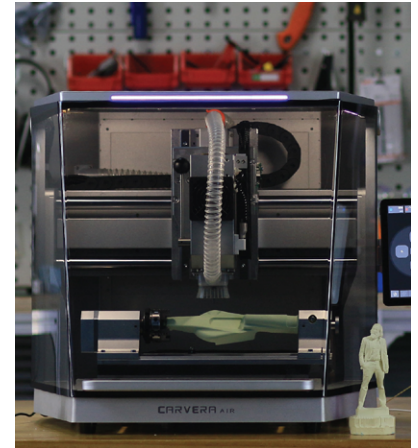
As students engage with the topics in this lesson, consider the following learning objects to measure student success:

- Students will solve a problem through the steps of an engineering design process.
- Students will effectively use CAD software to create a design or model that can be manufactured
- Students will effectively use CAM software and CNC machines to manufacture their designs
- Students will collaborate and provide feedback to their peers

Recommended Resources:

In order for students to be able to engage with the topics and activities in this lesson safely and effectively, there are a number of resources that may be needed, such as the following:

- A computer with Internet access to CAD and CAM software (*per student or group*)
- A CNC Mill, such as the [Carvera Air Desktop CNC](#) (*per class*)
- Material to fabricate projects with such as wood, acrylic, or soft metals
- Additional materials for prototyping, such as dowels, rods, markers, screws, and recycled materials to include in prototype fabrication



The Carvera Air Desktop CNC by Makera

We have also created a [planning document](#) for students to accompany this lesson, as well as a [rubric](#) for evaluation and assessment. You can also find tutorials on how to make mechanical tools such as the Trammel of Archimedes on the [Makera YouTube channel](#).

Adaptions and Modifications:

There are countless ways to adapt and modify this lesson based on the individualized needs of your students and your instructional space. Some possible methods include:

- Instead of all students creating the same mechanical tool, allow them to research and brainstorm their own unique ideas.
- Additional rapid prototyping machinery, such as 3D printers, may also be used to make parts for prototypes
- Beginners may need support in using CAD and CAM software, and choosing software that supports students at their experience level is key. Provide templates to support students as they begin their designs.

Cross-Curricular Connections:

In addition to engaging with content from within the STEM (science, technology, engineering, mathematics) disciplines, students may be challenged to incorporate art concepts and skills as they design and construct their prototypes, as well as literacy skills as they communicate their ideas and prototype to their peers. State standards may be able to be integrated into this lesson to support these objectives, as can the student learning standards and benchmarks from [ISTE](#) and [ITEEA](#):

- ISTE 1.1d Technology Operations
- ISTE 1.4.a Design Process
- ISTE 1.4.b Design Constraints
- ISTE 1.4.c Prototypes
- ISTE 1.4.d Open-Ended Problems
- ISTE 1.6.c Models and Visualizations
- STEL-1- Nature and Characteristics
- STEL-2- Core Concepts
- STEL-3- Integration of Knowledge
- STEL-7- Design in TEE
- STEL-8- Apply, Maintain, Assess

Teaching through a Design Process:

An **Engineering Design Process** is a tool utilized by engineers and designers to work through designing solutions to our everyday problems. From creating the next big product, to supporting infrastructure needs of a city, this process allows us to methodically work through developing prototypes to solve a problem in the best way possible. A design process can take many different forms with varying steps, but most start by identifying a problem and concluding with reflection. A key aspect to a design process is that there is no one solution to any problem, and each time we solve a problem we learn new things, allowing us to make improvements as we reflect and grow in our skill and understanding. By teaching through a design process, students will gain skills in creative thinking, communication, collaboration, and problem solving, preparing them for their future career, whatever that may be.



An example engineering design process by Makera

**STEP
1**

Define the Problem

Problem Statement:

While we have many computer-driven tools that allow for us to create precise designs and technical drawings today, early engineers like Archimedes needed to find their own ways to do the same. One such method was the Trammel of Archimedes, which is a tool that converts rotational motion to linear motion allowing for mathematically perfect ellipses to be drawn... something that could never be achieved freehand! Centuries later, you are now challenged to solve this problem around the specifications and the constraints of a real-world design challenge. Possible **constraints** for this challenge may include:

- You must design and develop a solution through the steps of an engineering design process
- Your prototype must be made using at least one CNC production technique
- Your prototype must have at least 3 parts
- Your prototype must include instructions on how it is to be used with accuracy

Career Connections:

The Trammel of Archimedes is an ellipsograph, which is a mechanism that generates the shape of an ellipse. Tools like these allow for designers and engineers to create precisely drawn ellipses for use in the develop of technical drawings mathematically expressions. These tools also influenced the creation of many measurement and calibration tools still used today, as well as the design and development of modern Computer-Aided tools, such as CAD software and CNC machinery. In addition to learning about these different tools and what tasks they allow us to perform, students are also engaging in the utilization of an engineering design process. These are real-world problem-solving methods and design techniques used in countless industries as the designers and problem solvers of today create the products we buy and use everyday.

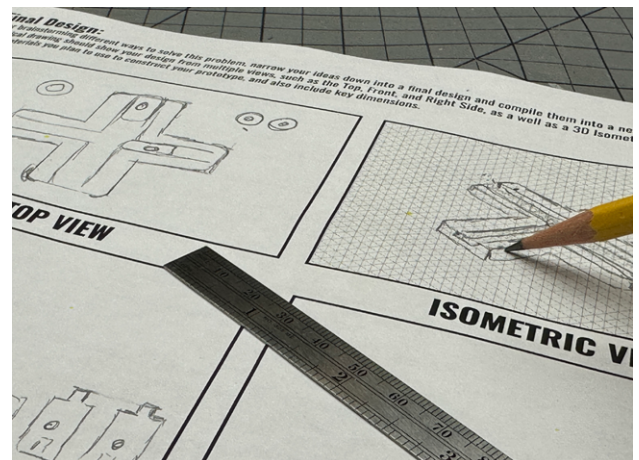
**STEP
2**

Brainstorm Ideas

Brainstorming Possible Ideas:

In this stage of the engineering design process, we must consider existing solutions and constraints as we brainstorm how we may solve this real-world problem. Students should first research the Trammel of Archimedes and other forms of ellipsographs, then work to design their own mechanical tool under the constraints of the challenge.

We recommend collecting our ideas through **thumbnail sketches**, then narrowing our ideas down into a final sketch or **technical drawing** before moving into the CAD stages.



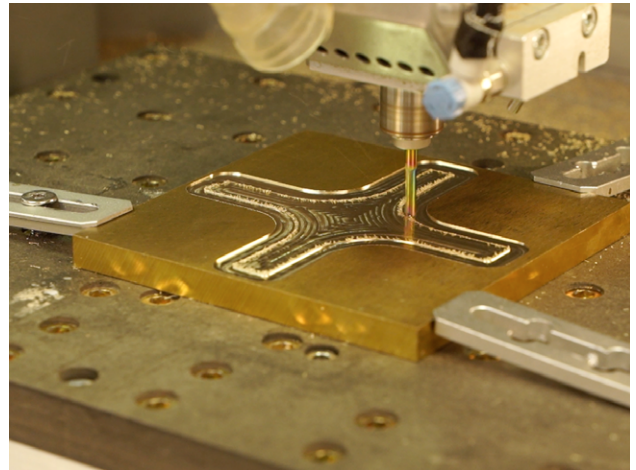
Brainstorming ideas using the planning document for this activity

STEP
3

Fabricate a Prototype

Designing for Subtractive Manufacturing:

As we transition to the fabrication stages of the engineering design process, we must first consider the constraints and limitations of the resources we have available to us. Material, or **stock**, is a key constraint, as well as the CNC machine and bits we may be using to manufacture our prototypes through subtractive methods. **Subtractive manufacturing** machines, such as the Carvera Air Desktop CNC, manufactures by removing, or subtracting, material using a cutting process. The precision capable is dependent on the precision of the machine, bits used for cutting, and the material being used.



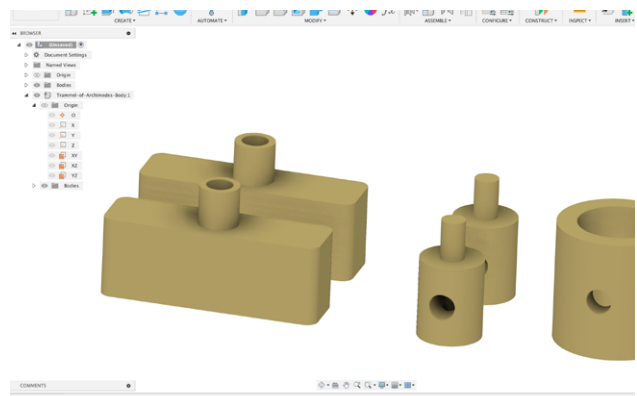
The Carvera Air CNC machining a mechanical part out of solid brass

We recommend using softer materials like epoxy tooling board or machinable wax for prototyping our models before machining with harder materials like woods, composites, and metals. This allows for mistakes to be made without risking damage to cutting bits or the machine, and provides a supportive environment for students to learn in. Students must also know what **bits** they have available to them as this sets the **tolerance** of their designs. For example, if students had access to a 3.175mm (1/8") cutting bit that was 25 mm in length, we could create pockets or holes in our parts that was 3.175 mm in diameter, or larger, as well as in material that was 20 mm thick. But we couldn't use this bit to make a 1.5 mm hole, as this bit is too large. Fortunately the Carvera's automatic tool changer and the Carvera Air's tool-less tool changer makes swapping bits easy to do, but we must always consider what resources are available in the design stages.

Creating a Design in CAD:

After considering the resources available, we can move into developing our designs using **Computer Aided Design** software, or **CAD**. There are countless CAD programs available to students, and CNC machines like the Carvera Air can work with design files created in 2D or 3D file formats, accommodating a wider range of programs and projects.

Choosing the right CAD program will vary based on the constraints of the challenge, the types of projects you are looking to create, and most importantly, student prior understandings and abilities. For younger students, we recommend using CAD programs like Autodesk [Tinkercad](#) to get started in designing 2D or 3D models for production.



Designing a Trammel of Archimedes in Autodesk Fusion

For more advanced students, CAD programs like Autodesk [Fusion](#), [Onshape](#), or [Solidworks](#) will not only offer a wider range of what's possible through more advanced tools and features, but through industry connections to possible careers as well! After developing a design in CAD, a design file needs to be exported and brought into CAM as discussed in the next step. Typical file formats that are accepted in CAM programs include STL or STEP for 3D files and DXF or SVG for 2D files, though this will vary based on the CAM program you choose to use.

Preparing our Designs in CAM:

After creating and exporting a design file in CAD, we must import that file into **Computer Aided Manufacturing Software**, also known as **CAM**. Like CAD, there are many different CAM programs available which support a wide range of projects and student needs. Fortunately, the Carvera and Carvera Air are both designed to support a wide range of CAM programs right out of the box! You can learn more about the CAM programs supported by the Carvera on the [software page](#) of the Makera website. In general, we recommend using [Makera CAM](#) for its versatility, intuitive tools, and ease of use for Education settings.

For whichever CAM program you choose to use, the steps for preparing our designs to be manufactured is very similar. As an example, this lesson will show the steps for creating the Trammel of Archimedes in Makera CAM:

1 - Setup our project:

The first thing we must do is setup the CAM project to match the resources we have available. Makera CAM is designed for the Carvera and Carvera Air, but we still must choose the right material and size for our stock before importing our design files.

2 - Create Tool Paths (Operations):

For every cut, we must create an operation or tool path. This tells the Carvera Air what bit to use, as well as where and how it should cut our stock to create our model. As we create our tool paths, there are a few key things to consider:

2D or 3D: Makera CAM allows for you to create both 2D and 3D operations. The correct operation will typically depend on the type of design you import, as well as the type of cutting path you need to create in order to make your design.

Bits (Tools): This is the tool that will be used to create the cut within this tool path. Bits that come with the Carvera Air are already loaded in Makera CAM.

Feeds and Speeds: These are the parameters that set how quickly the tool will cut our stock. These feeds and speeds must be set based on the type of tool we are using, as well as the stock we are using.

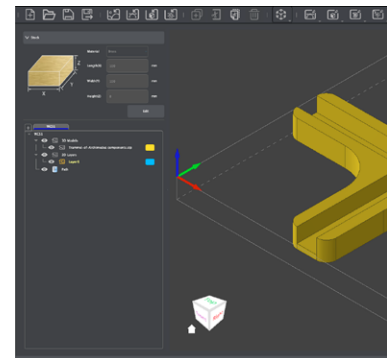
Tabs: Whenever we are cutting all the way through our stock, we must ensure that we create tabs so that our part does not break away or eject during the machining process. Alternatively, double-sided tape may be used instead.

3 - Simulate:

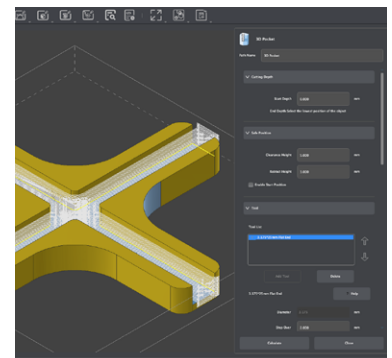
A key strategy to effectively use CAM is to simulate our designs as we create our tool paths. This will allow for us to inspect our designs for any possible issues that may occur during the manufacturing stages.

4 - Export as a Gcode file (Post Process):

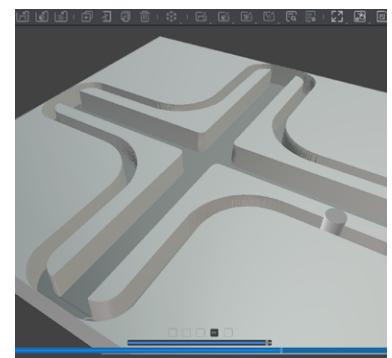
Once all operations have been created, we can compile them into a Gcode file automatically formatted for the Carvera and Carvera Air. This file can then be uploaded to the Carvera Air for manufacturing via the Makera Controller App.



Setting up a project in Makera CAM



Creating 3D Pocket operations in Makera CAM



Simulating Tool Paths in Makera CAM

Tutorials on how to prepare a design to manufactured in CAM for the Carvera can be found on the [Makera YouTube Channel](#).

Safety First:

As we transition into fabricating and constructing our prototypes, the most important thing to consider is **safety**. Always ensure students are properly trained to work with the tools and machines available to them, and provide guidelines to create a safe environment. CNC Machines should not be left unattended and should be operated with the lid closed. A vacuum and dust collection system, like the [Cyclone Dust Collector](#), should be used to remove dust particles created during the machining process. And proper ventilation and eye wear must be used whenever working with laser engravers.

Fabricating our Prototypes:

After creating a Gcode file using CAM software as discussed earlier, we can manufacture our designs using a CNC mill like the Carvera Air. Before we begin to run our jobs, we must properly secure our stock on the bed of our machines. **Wasteboard** should be used below our stock whenever we plan to cut all the way through so that we protect the bed of our machine. We should also align our stock with a corner clamp in one of the anchor positions, as well as secure it using top or edge clamps before moving onto starting the job. ([Securing Stock Tutorial Video](#))

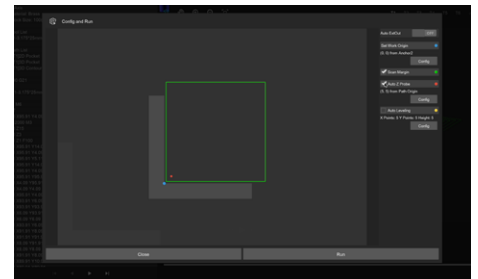


Securing Brass Stock to the bed of the Carvera Air CNC

The Carvera and Carvera Air uses the [Makera Controller app](#) to setup and run our Gcode files, and there are a few key things that should be considered before running our jobs:

Work Origin:

We need to ensure that our design is going to be machined in the correct location. We can adjust the offsets of our work origin to make sure that the design will align with our stock.



Configuring our job in the Makera Controller App

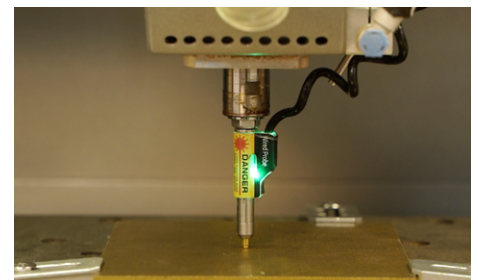
Scan Margin:

By enabling this feature, the Carvera Air will trace the perimeter of our part before machining so that we may ensure that it is in the correct location and avoid accidental collisions.

Auto Z Probe ([Auto Z Probe Tutorial Video](#)):

By enabling this feature, the Carvera Air will use the Wired Z Probe to measure the height of our stock automatically. Alternatively, we could use the manual XYZ probe to determine the stock height and position.

([Manual XYZ Probe Tutorial Video](#))

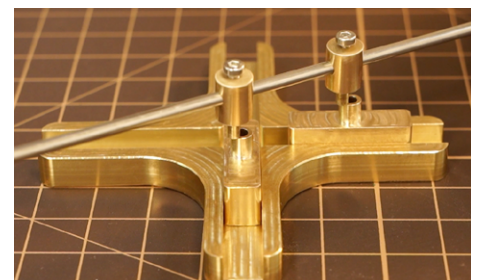


Automatically Measuring the height of the stock with the Carvera Air's Wired Z Probe

Auto Z Leveling ([Auto Z Leveling Tutorial Video](#)):

This feature can be used if there are deviations in the thickness of our stock, such as warped material or rough cuts. The Carvera Air will automatically measure the deviations in stock thickness and compensate for them while machining.

After machining our parts using a CNC machine, we may need to create other parts for our prototypes using traditional materials processing methods, or other CNC machines like 3D printers or lasers. Once all parts have been created, we can work to safely assemble our prototypes before moving into the testing stages of the design process.



Assembling the Trammel of Archimedes

STEP
4

Test and Evaluate

Strategies for Testing and Evaluation:

In this crucial stage of the design process, we must test and evaluate our prototype solutions to determine if they were successful based on the specifications and constraints of the challenge. For the Evolutionary Ellipsographs lesson, students must determine how effective their mechanical tools are, as well as the prototypes developed by their peers through a real-world experience.

Challenge students to offer constructive feedback to their peers as they evaluate one another's prototype solutions. Throughout this process, possible things to consider include:

- Does the prototype meet the constraints of the challenge? (Size, material, parts)
- How well does the prototype function? Does it operate as intended?
- How reliably does the prototype work? Will it continue to perform accurately after repeated use?

And remind students that a failed prototype does not mean we failed! Making mistakes are a key step in the design process as we learn and improve our ideas through redesign and reflection.

STEP
5

Redesign

Methods for Redesign and Reflection:

While this may be the final step of our design process, it certainly is not the final step in prototyping and creation as there is always room to improve. As we develop prototypes, test and evaluate our creations, and obtain feedback from our peers, we can work to develop models that work better, are more aesthetic or ergonomic, or perhaps made more efficiently. While we may not have time to engage with redesigning and recreating our prototypes in an education setting, we must always make time to discuss this important step and allow students to consider how they would improve if they had the opportunity to do this project again.

Challenge students to share their thoughts for reflection through a summative assessment, such as an exit ticket. Or perhaps by creating a sketch of their redesigned solution, or even a refined model using CAD. If time permits, allowing students to apply what they have learned to create a revised iteration of their prototype may be both a meaningful learning experience, and also one that creates strong career connections and fosters greater problem-solving abilities too.