# Machining Puzzles and Games

Difficulty Level: Beginner

Duration: Approximately 5 Classes

Lesson Overview:

In the Machining Puzzles and Games lesson, students are challenged to design a prototype of a desktop puzzle or game that meets the specifications and constraints of a real-world design challenge. Through a project-based approach, students will engage through the steps of an engineering design process as they research existing solutions, brainstorm new possible ideas, develop a design using software, fabricate their own designs using CNC machines, and then test, evaluate, and reflect upon what they are able to create.
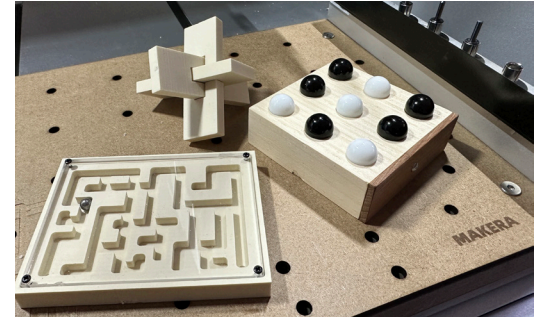
Click here to view the overview video for this lesson on the Makera YouTube channel.

Pacing Guide:

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

DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
Begin by introducing the design challenge, create career connections, and start the brainstorming stages of the design process.	Allow students to transition from the brainstorming stages to the fabrication stages as they develop their designs using CAD software.	Complete CAD designs started previously, introduce subtractive manufacturing and CAM stages (if applicable). Prepare designs to be manufactured in CAM.	Manufacture projects using CNC machines, such as the Carvera, as well as any additional resources available to students.	Finish assembly, then test and evaluate under the constraints. Lastly, allow for students to reflect through the Redesign stages of the design process.

Essential Questions:

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

- Why do we buy toys, puzzles, and games?
- Who designs the puzzles and games we buy?
- What makes a puzzle or game entertaining and engaging?
- How are products like puzzles & games 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 Desktop CNC *(per class)*

- Material to fabricate projects with such as wood, acrylic, or epoxy tooling board

- Additional materials for prototyping, such as marbles, string, cardboard, paper cups, hot glue, fasteners, and recycled materials to include in prototype fabrication

The Carvera 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 example puzzles and games such as a tic tac toe board, mini maze, or 3D knot puzzle 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:

- In addition to using a CNC mill to manufacture projects, consider incorporating traditional manufacturing tools like hot glue guns, drill press, x-acto knife, or saw.

- 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 utilize 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

STEP 1 — **Define the Problem**
What problem are we challenged to solve, and what are the specifications and constraints of the challenge?

STEP 2 — **Brainstorm Ideas**
How has this problem already been solved before, and how may we solve it differently under our constraints?

STEP 3 — **Fabricate a Prototype**
What materials and resources can we use to safely fabricate a prototype solution to this problem?

STEP 4 — **Test and Evaluate**
Do our prototypes function as designed? And do they meet the specifications and constraints of the challenge?

STEP 5 — **Redesign**
Looking back on the prototypes we created, what improvements could be made based on what we learned if we were to do this again?

ENGINEERING DESIGN PROCESS — MAKERA Lesson Plans

An example engineering design process by Makera

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.

STEP 1 Define the Problem

Problem Statement:

Students, have you ever been bored? Studies show that we all become bored at times, how can this be solved? A toy and game company would like to create pocket-sized puzzles and games catered to the interest of students and young adults like you! Thanks to your knowledge in design and prototyping techniques, you have been hired by this toy and game company to solve this problem. As the designers for these future products, we must ensure that we work around the specifications and the constraints of the client to find success. Possible **constraints** for this challenge may include:

- Your puzzle / game must include at least 3 parts
- Your puzzle / game must be made using at least one CNC production technique
- Your puzzle / game should not exceed 6" x 6" x 6" in overall volume (152.4 mm x 152.4 mm x 152.4 mm)
- Your puzzle / game should take at least 15 seconds to solve, and include instructions on how to play for your users

Career Connections:

The global puzzles and games market was valued at approximately $15 billion dollars (US) in 2022, and is expected to grow by an additional $3 billion over the next 10 years. Puzzles and games are enjoyed by all ages, and there are different marketing strategies that can be utilized to cater to different user groups. Creating a successful puzzle and game is a unique design challenge as the creators must not only design a product that is aesthetically pleasing and durable so that it withstands continued use, but also create one that is engaging and challenging as well. Furthermore, the challenge and the objectives must be made clear to the user or else the product might fail all together. Prototyping stages, including test groups and feedback, is a key strategy towards developing a successful product!
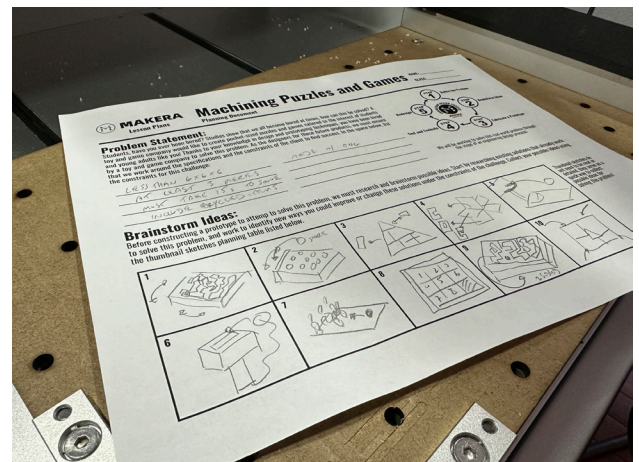
STEP 2 Brainstorm Ideas

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 existing solutions and learn from the products already available, then utilize these items as inspiration as they design their own unique prototype solutions under the specifications and constraints of this activity.

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

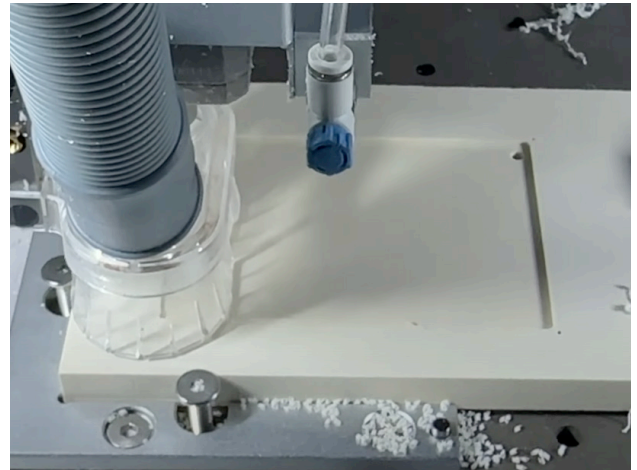*Brainstorming ideas using the planning document for this activity*

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 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.

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

The Carvera CNC Machining a Maze Game out of Epoxy Tooling Board

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 whats 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 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.
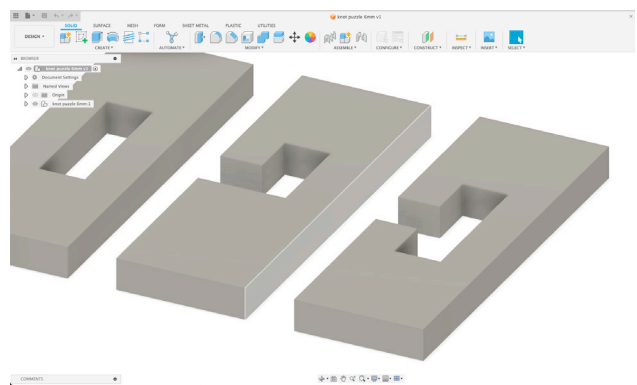
Designing a 3D Puzzle in Fusion 360

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.

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 a puzzle in Autodesk Fusion:

1 - Setup our project:
The first thing we must do is setup the project so that we are using the correct profile for the Carvera, as well as set our work origin to the top left corner of the stock. This will ensure that the file we create is compatible with our machine.

2 - Create Tool Paths (Operations):
For every cut, we must create an operation or tool path. This tells the Carvera 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:

Setting up a project in Fusion 360

Bits (Tools): This is the tool that will be used to create the cut within this tool path. Bits that come with the Carvera can be imported into all supported CAM programs.

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. Click here for recommended feeds and speeds for the Carvera.

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.
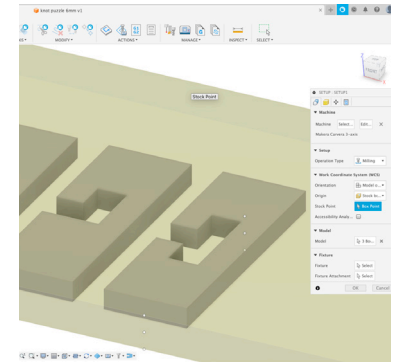

Creating a 2D contour operation in Fusion 360

Multiple Passes: If we are cutting through thicker stock, we want to do this in multiple depths so that we do not break our bit. We also may want to consider creating roughing passes with a larger bit, then finishing passes with a smaller bit for a higher quality finish and more efficient machining.
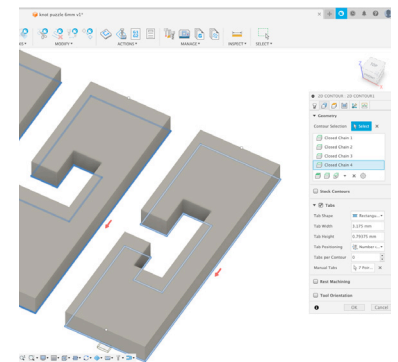
3 - Simulate:
A key strategy to effective use CAM is to simulate our designs as we create our tool paths. This will allow for us to inspect our designs for any possible issues that may occur during the manufacturing stages.

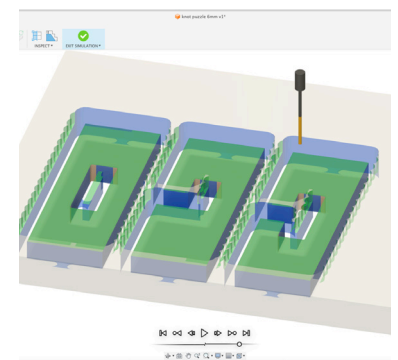**4 - Export as a Gcode file (Post Process):**
Once all operations have been created, we can compile them into a Gcode file formatted using the Carvera's profile. This file can then be uploaded to the Carvera for manufacturing via the Carvera Controller App.

Simulating a design in Fusion 360

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 think 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 one built into the Carvera, 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. Before we begin to run our jobs, we must properly secure our stock on the bed of our machines. **Wasteboard** (spoilboard) 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**)
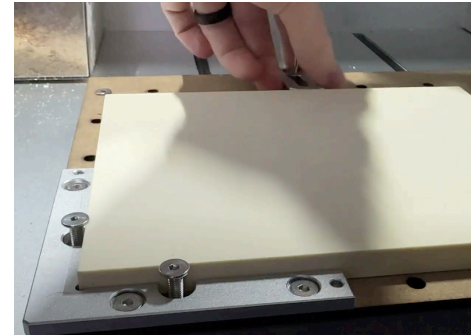
Securing Stock to the bed of the Carvera CNC
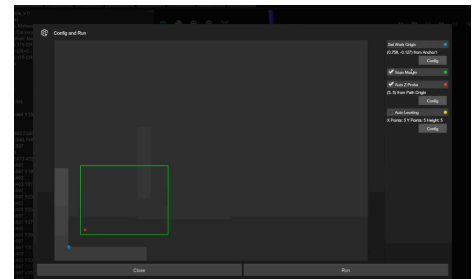
The Carvera and Carvera Air uses the Carvera Controller app to setup and run our Gcode files, and there are a few key things that should be considered before running our jobs:

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 Carvera Controller App
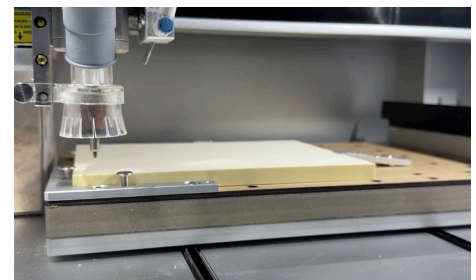
Scan Margin (Scan Margin Tutorial Video):
By enabling this feature, the Carvera will trace the perimeter of our part before machining so that we may ensure that it is in the correct location and not going to collide with any clamps.

Auto Z Probe (Auto Z Probe Tutorial Video):
By enabling this feature, the Carvera will use the Wireless 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**)


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 will automatically measure the deviations in stock thickness and compensate for them while machining.

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

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.
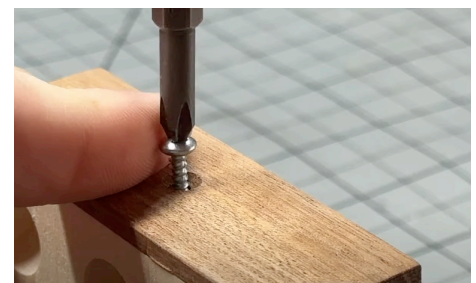
Assembling the parts of a tic tac toe game using screws

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 Puzzle and Game project, this is an exciting opportunity for students to test their games, 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 does the prototype look? Would it catch our interest as a consumer?

- How hard or easy is it to play the prototype? Are the instructions clear? And is it engaging?

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.

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Machining Puzzles and Games
Written by Jason Erdreich
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