Robotics 311 : How to build robots and make them move

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ROB 311 – Lecture 8

- Today:
  - Review Additive Manufacturing
  - Discuss best practices
  - Discuss laser cutters
  - Quiz

- Announcements
  - HW 2 will be posted today
  - Would you rather have a STL file of the ball bot or a robotic leg?

Manufacturing Types

"spec'ing"
This happens first

Now you know:
- Torques
- Speeds
- Ratio
- Rough sizing

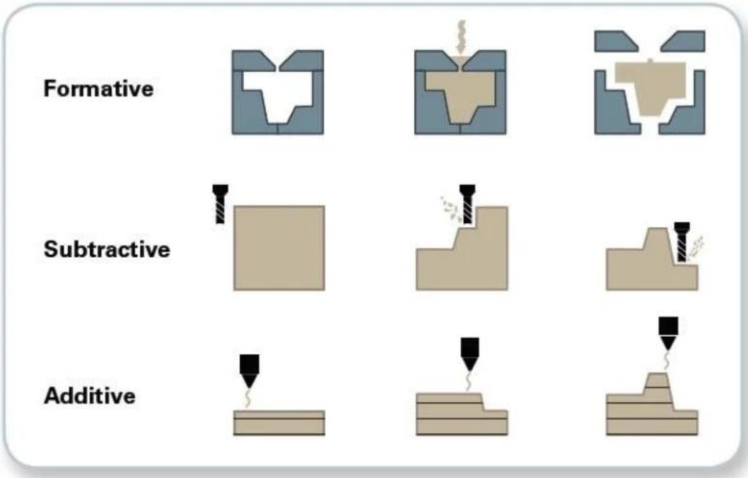
Upcoming focus of the class

Transmission – Ratio, Efficiency → **Brushed electric motor** – Motor properties → **Heat production** – Thermal properties → **Physical Design** – Layout, Manufacturing

- So far, we have spec'd the components – we've chosen the architecture and now we need to make it a reality
- This includes choosing the physical layout, solid modeling, creating design files, and manufacturing
- We will go over *manufacturing* first for the sake of lab
- There are three types of manufacturing
  - Formative
  - Subtractive
  - **Additive**

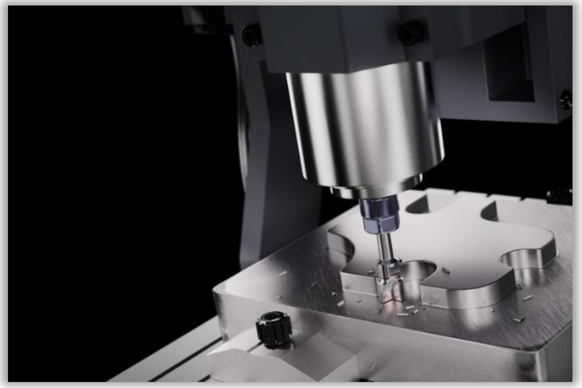
Some

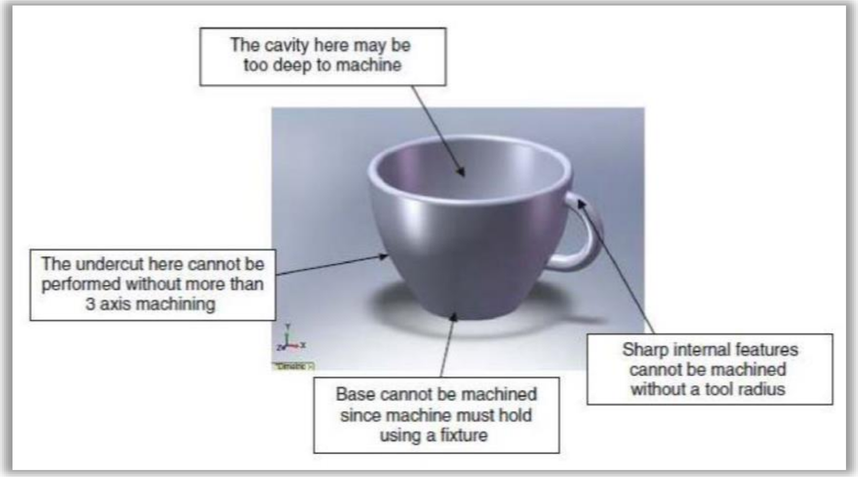
What we will focus on in this course



Milling

- Completed by a spinning bit (end mill bit)
- Parts with more complex geometries require milling from many directions
- 3-axis vs. 5-axis mills
- Factors into design ← Factors in less for 5-axis milling but parts cost more $$$
  - Hole depths, undercuts, etc.
- 'Quick' / economical machine shops in China
- Milling and lathing are considered 'traditional manufacturing' methods





Turning / Lathing

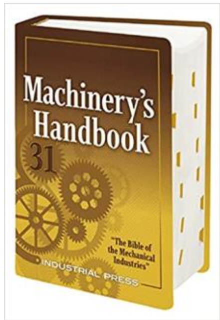
- Lathing – cutting or shaping with a *lathe*
  - Completed rotating a part and cutting at a radius
  - Other uses – woodworking / prototyping
- Design decisions can be made to take advantage of rapid prototyping tools
  - We are using laser-cut acrylic for this reason
- Another design consideration is fit or *tolerance*
  - CNC machining tolerance chart provided below
  - We'll refer back as we learn more about 3D printers
  - Extra space needed for holes / pins, sliding fits, etc.

ISO standard 2768

LINEAR DIMENSIONS:

Permissible deviations in mm for ranges in nominal lengths	f (fine)	Tolerance class designation (description)		v (very coarse)
		m (medium)	c (coarse)	
0.5 up to 3	±0.05	±0.1	±0.2	-
over 3 up to 6	±0.05	±0.1	±0.3	±0.5
over 6 up to 30	±0.1	±0.2	±0.5	±1.0
over 30 up to 120	±0.15	±0.3	±0.8	±1.5

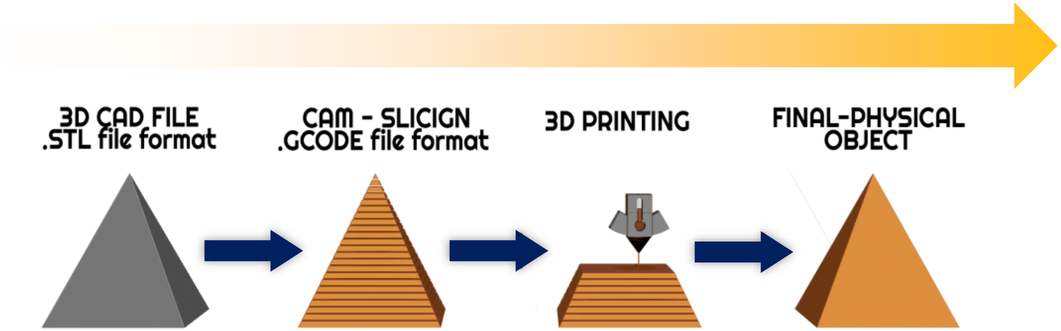
Tolerances also provided in large tables in this book



DIN ISO 2768 tolerance chart uploaded to Canvas/Resources as a guide

Additive Manufacturing / 3D Printing

Digital file created in Solidworks

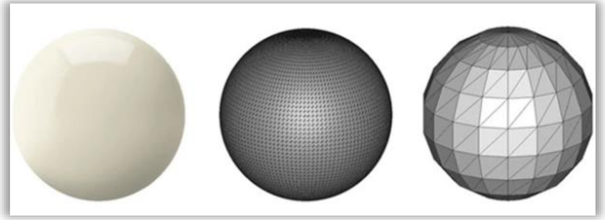


Prototype part ready for use

Slicing software
.STL → .gcode

3D printer firmware accepts
.gcode and creates tool paths

- To use a 3D printer, first a part file is needed that's exported as a .STL file
- The .STL file contains polygons that 'digitize' the shape
- More polygon elements mean a larger .STL file (usually kB to MB)
- This .STL needs to be transformed into printing instructions (G-code)
- Slicing operations will likely be performed by Alyssa / Makerspace
- Layering is separate from polygon size in STL



Example showing STL resolution polygon size differences

Slicing Software

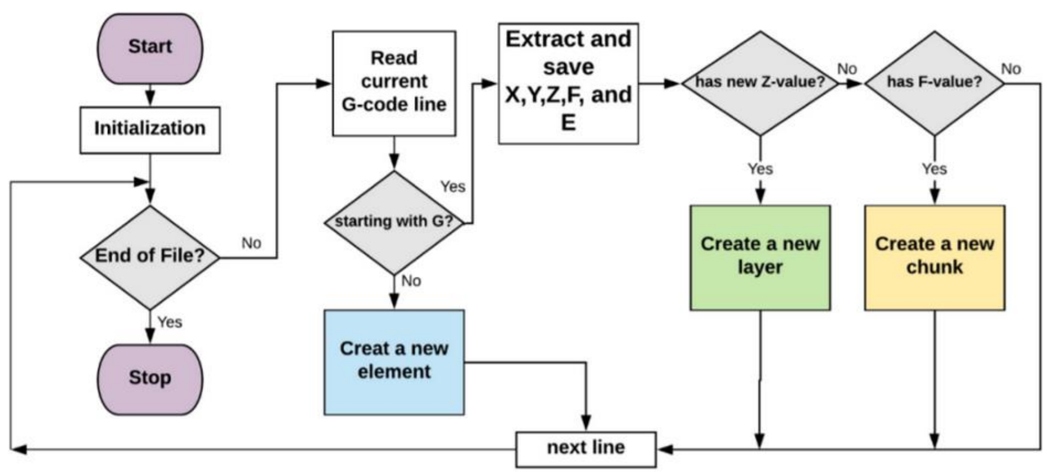
- A .gcode file is series of commands that tells the 3D printer what actions to perform—where to move, how fast, what temperature to set, etc.
- Each 3D printer expects the .gcode file to be formatted in a specific way based on the printers firmware.
- Two of the most common printer firmwares are RepRap and Marlin.

```
M107
M104 S30 ; set temperature
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle

; Filament gcode

M109 S30 ; set temperature and wait for it to be reached
G21 ; set units to millimeters
G90 ; use absolute coordinates
M82 ; use absolute distances for extrusion
G92 E0
```

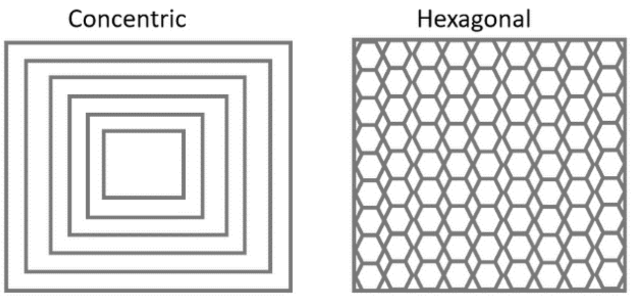
Example G-code snippet



G-code is read in a defined way that executes printing each layer

Slicing Software

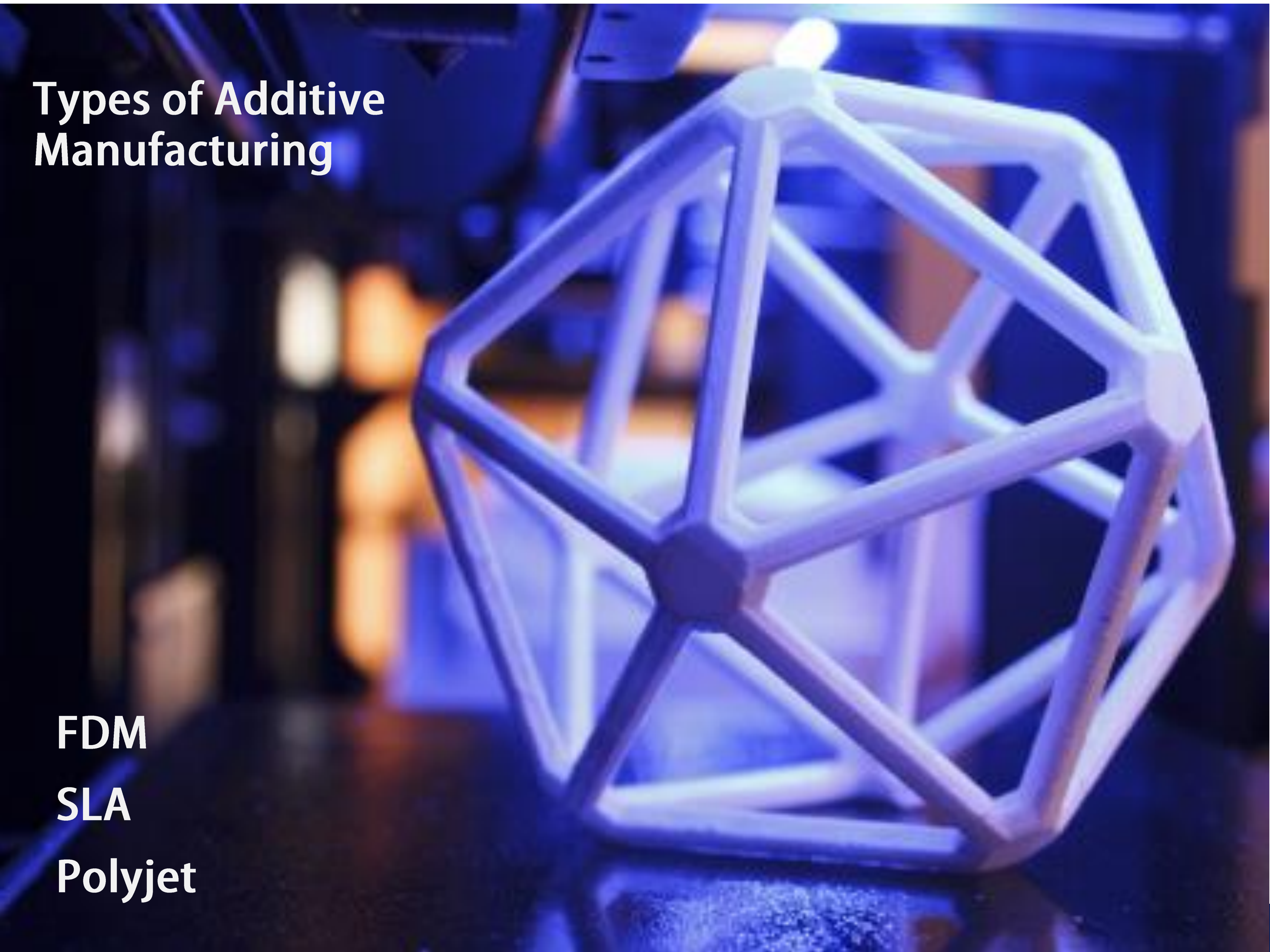
- Key functions of the slicing software is the infill pattern and layer height
- Infill – pattern of interior / structural plastic inserted
- Thicker infill for parts with greater loads
- Different types of infill based on part geometry
- Infill automatically created and with required tool paths
- Print speed is affected by layer height
- Print speed can be optimized based on are of the part (infill or outward facing)
- Most common (open-source) slicing software is Cura



Example infill patterns

Cura slicing software provided by Ultimaker

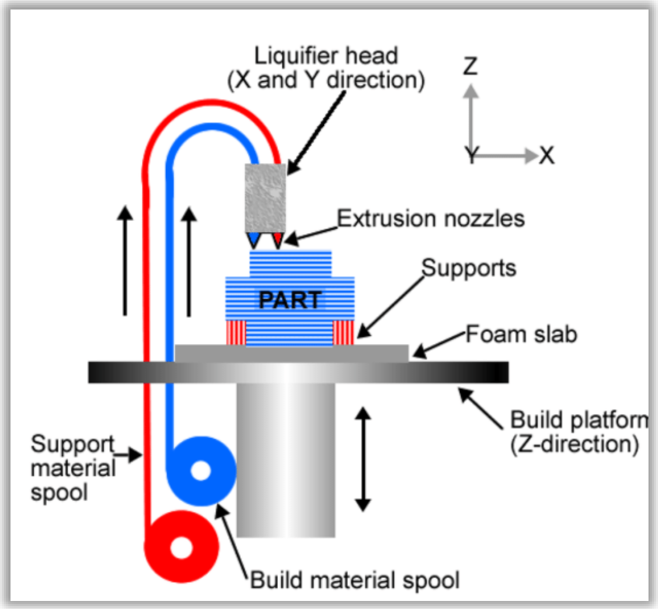
Types of Additive Manufacturing



- FDM
- SLA
- Polyjet

Fused Deposition Modeling (FDM)

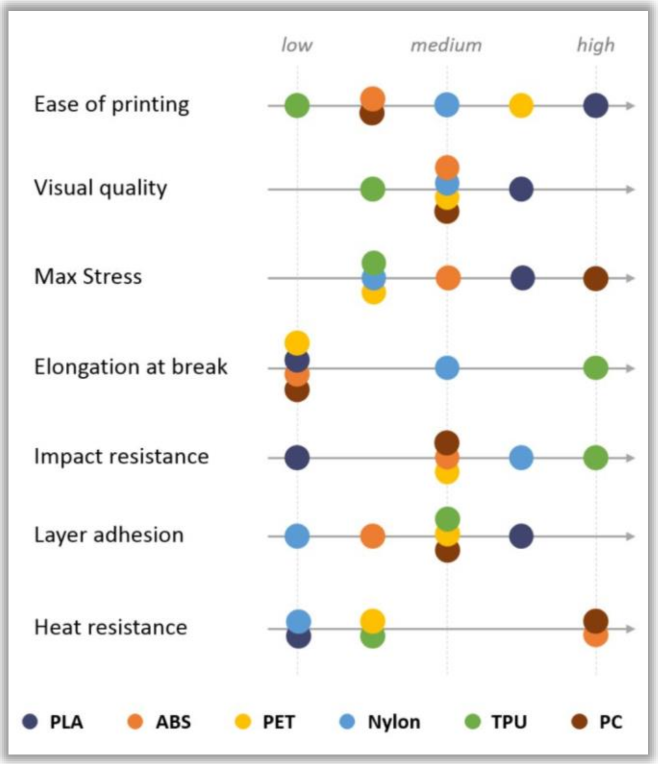
- One of the most common types 3D printers
- Heated plastic filament is extruded through a nozzle
- Common plastics: ABS, PLA, nylon
- Uses support material alongside build material to support parts they print
- Costs $100s to $10,000s



- Characteristics:
  - Layer thickness: 0.1mm ~ 0.5 mm
  - Build volume: 10 x 10 cm^2 ~ 50 x 50 cm^2+
  - Materials: next slide
  - Composite available
    - Continuous
    - Chopped

Fused Deposition Modeling (FDM)

- **PLA** – Thermoplastic monomer that is strong and easy to print, nice finish, good UV resistance
- **ABS** – Better temp resistance than PLA with higher toughness, can be processed with acetone for gloss finish
- **PET** – Heavier than PLA and ABS, with high chemical resistance
- **Nylon** – Strong material with some anisotropy. Mixed with glass or carbon fiber in Markforged



3D Hubs

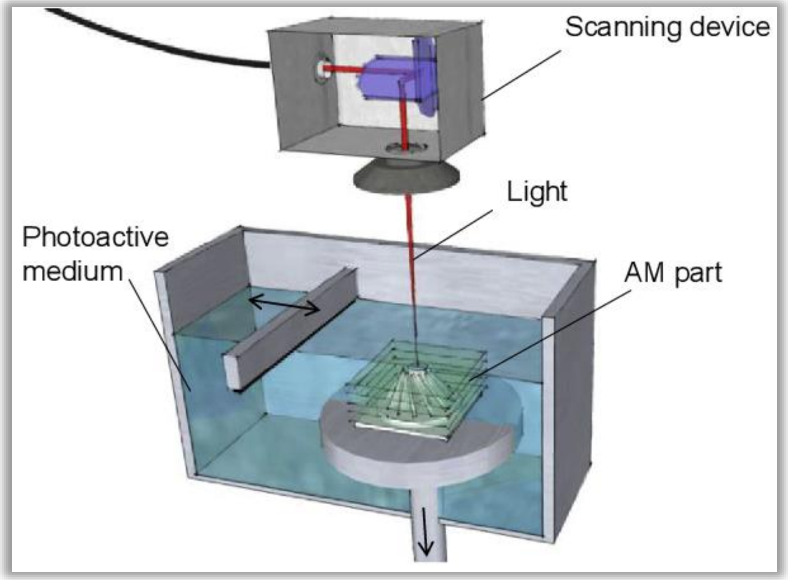
$800 Prusa (ABS)

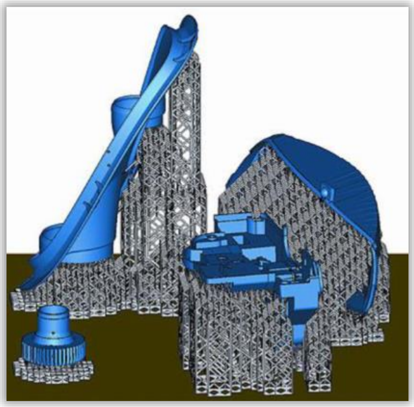
$50k Markforged (Onyx) - with continuous fiber composite reinforcement

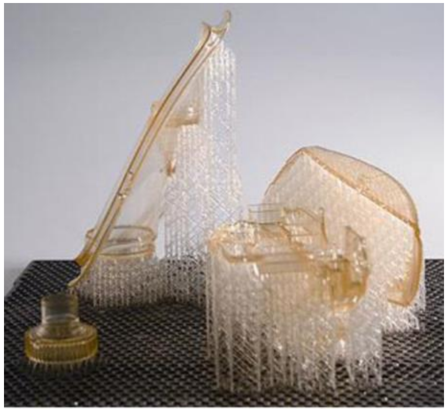
Stereolithography (SLA)

Formlabs Form 3

- SLA uses a liquid photoactive resin
- Laser cures / solidifies a thin layer of material at the focused depth
- The part descends (rather than the part building up)
- Support structure is built like a lattice and broken off
- Cost: \$100+
- Layer thickness: 50 μm
- Build volume: can be very large
- Materials: photopolymers (clear, opaque, range of material properties)
- Variants on SLA printers (DLP) – faster by using an image not a laser

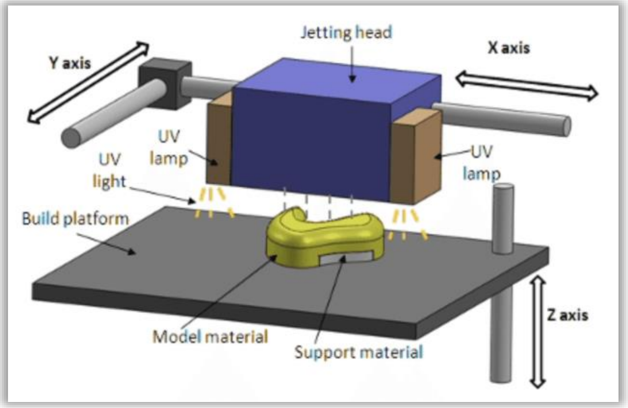






Polyjet Printers

- Polyjet printers print like an inkjet printer
- They spray material and cure with a UV light
- Invented by Stratasys
- Benefit: multiple colors and hardness / durometers
- Rubbery parts
- Support material often removed with ultrasonic water bath
- Cons: Parts are UV sensitive and get brittle
- Cost: $100+
- Layer thickness: 10s of μm
- Build volume: up to ~100 x 100 cm
- Materials: photopolymers (clear, opaque, range of material properties)



Stratasys Connex 500

Additive Manufacturing

- Overview

FDM

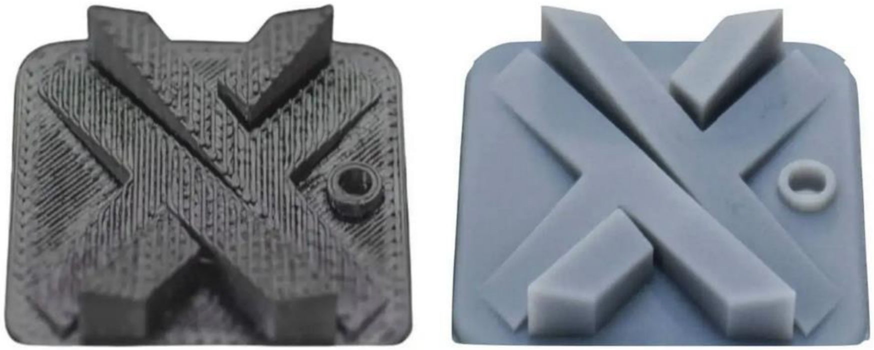
Parameter	Value
Tolerance	±0.3% (± 0.3 mm for 100mm)
Build volume	up to 914 x 610 x 914 mm
Layer thickness	~0.05-0.3 mm
Minimum feature size	up to 0.2mm

SLA

Parameter	Value
Tolerance	±0.2% (± 0.2 mm for 100mm)
Build volume	up to 736 x 635 x 533 mm
Layer thickness	~ 0.02
Minimum feature size	0.1mm

Polyjet

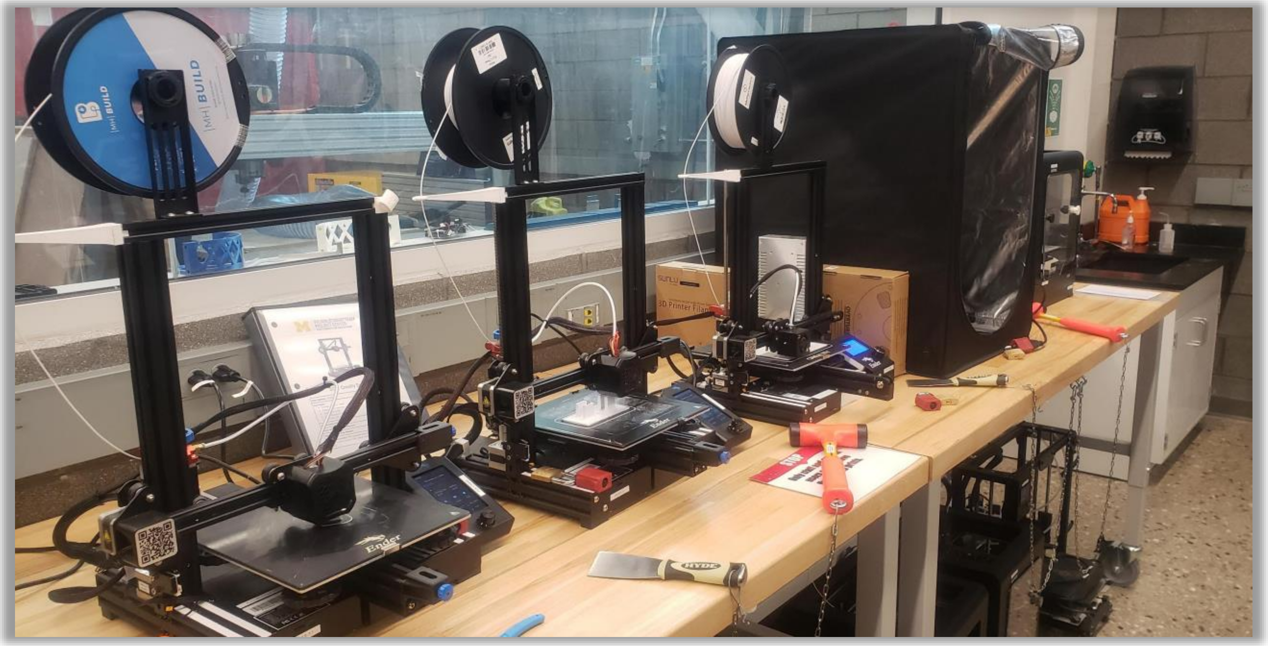
Parameter	Value
Tolerance	±0.05-0.1mm for 100mm
Build volume	up to 490 mm x 391 mm x 200 mm
Layer thickness	0.004 mm
Minimum feature size	1.2 mm or greater for rigid. 2 mm or greater for rubber-like



FDM vs. SLA

Where to 3D Print

- Printers are located in FRB Makerspace
- 3x Creality Ender 3 (FDM)
- You will have to use slicing software (Cura)
- Save .gcode to SD card -> insert into 3D printer
- Manuals uploaded to Canvas\Prototyping Machine Instructions
- PLA filament – provided for free
- Layer thickness: .1 - .4 mm
- Print size: 220 x 220 x 250 mm



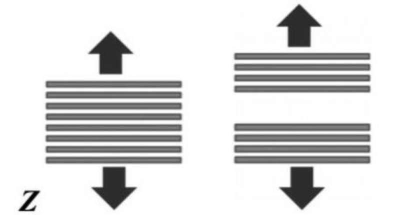
FRB Makerspace
1141 FRB

Load .gcode onto SD card and insert into printer

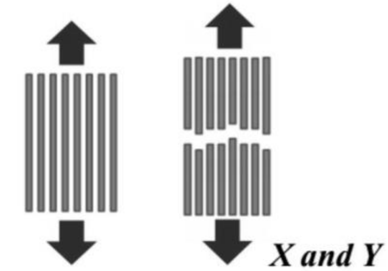
Best Practices – General

- Design considerations
  - Minimize volume of support structure
  - Check that support structures can be easily separated
  - Add tolerancing to the parts before slicing
  - Minimize overall print time
  - Maximize stiffness and minimize volume
- Slicing considerations
  - 3D printers create parts that are inherently anisotropic
  - Stronger in X-Y direction due to layer separation
  - Orient the part such that printing maximizes strength in desired directions
- Infill considerations
  - Always use an infill percentage < 60%

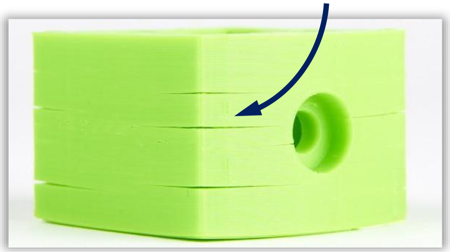
Weaker in Z direction (vertical)



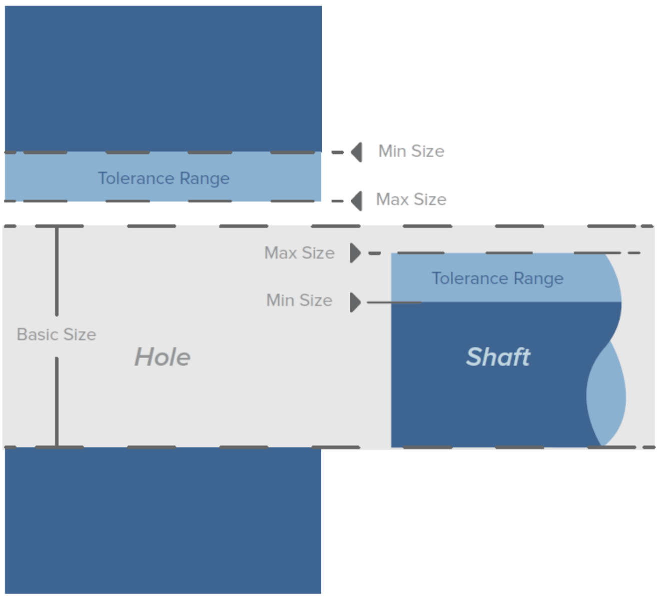
Stronger in X-Y direction in build plane

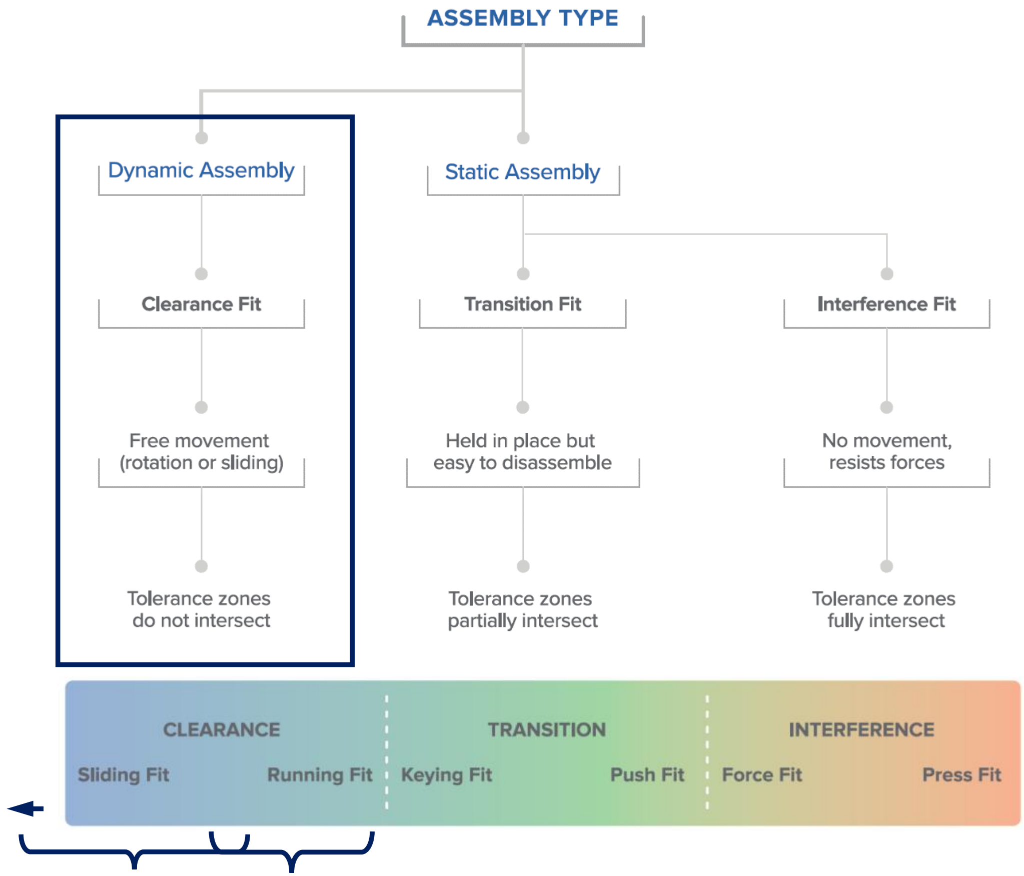


Layer separation



Best Practices – Tolerancing





Rapid prototyping tolerances

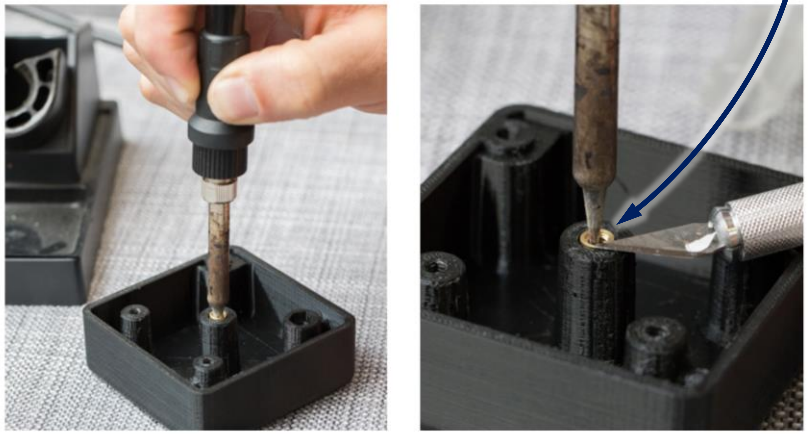
Traditional manufacturing tolerances (for research prototypes)

- You may need to add 0.2 - 0.3 mm to diameter of parts that rotate (OD)
- You may need to add 0.1 mm for clearance holes
- Layers compress to make holes smaller in FDM printing

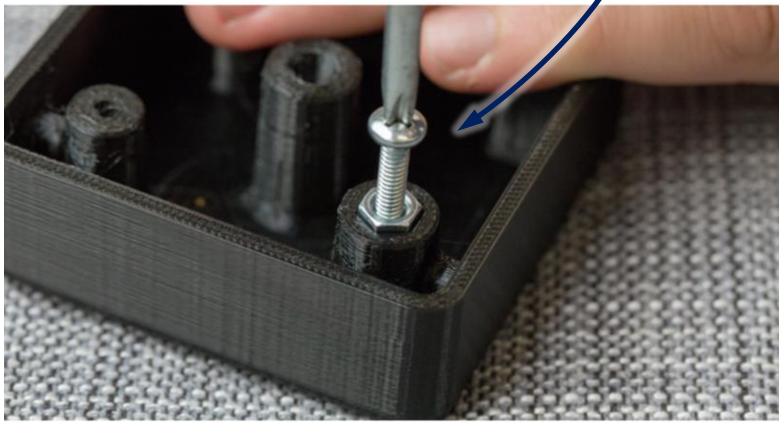
Best Practices – Fasteners

These are awesome (demo!) and should be used whenever possible

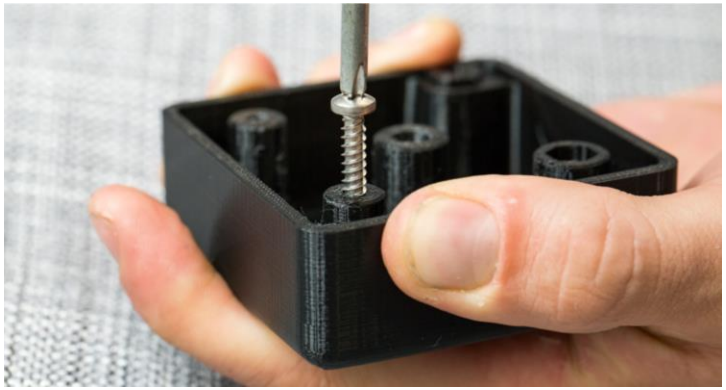
We used mostly these in our ball-bot



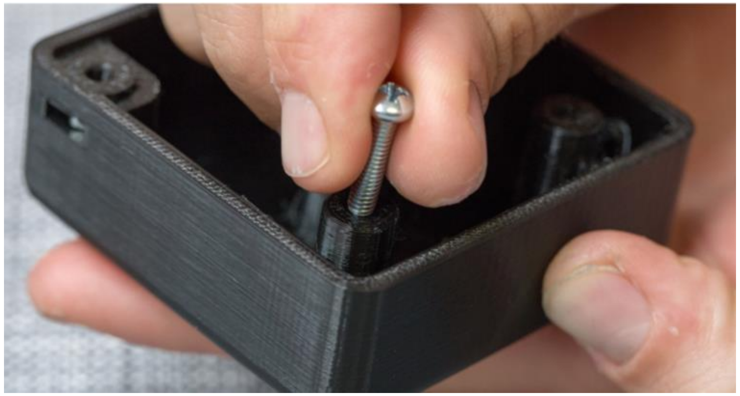
Threaded inserts can be heated and installed in a part. They come in both metric and English sizes. A soldering iron can be used to heat the insert for installation. Simple and robust.



Hex nuts can be designed to be captured in the part, so additional tools are not needed.



Self-tapping screws can be used to provide a secure fit. Inserts and hex nuts will be more robust and easier to assemble / disassemble.

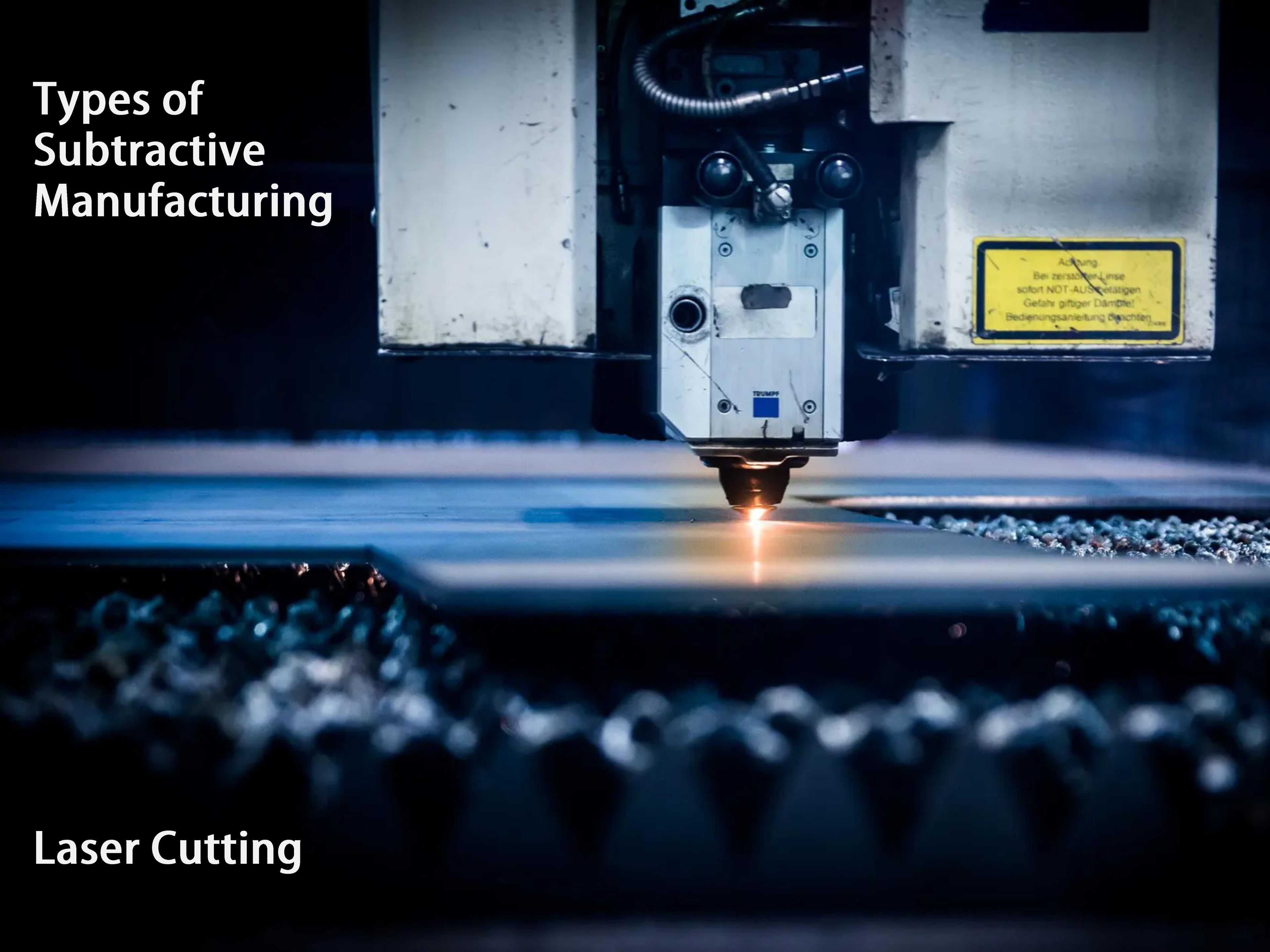


Machine screws will provide the lightest hold and should be avoided. Much shallower thread depth compared to the self-tapping screw. SLA can be tapped in solid modeling but use other methods, if possible.

Best Practices – Where to Get Solid Models

- Many times you may want to make something that requires the solid model of something common
  - iPhone, body parts, characters, etc.
- Repositories exist where you can download / view solid models
  - www.grabcad.com – online repository with 1.3M+ solid models
  - www.thingiverse.com – online repository with millions of STL files
- With the 3D printing instructions, you can just download and print!

Types of Subtractive Manufacturing

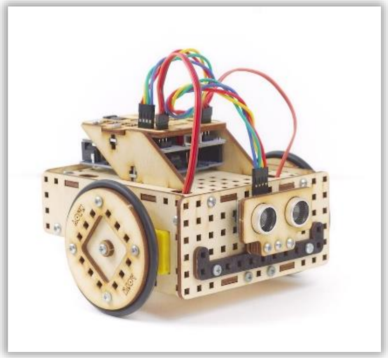


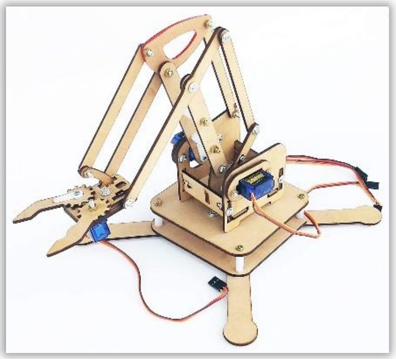
Laser Cutting

Subtractive Manufacturing

- 3D printing is a key aspect of rapid prototyping, and some methods from subtractive manufacturing are also quick and easy
- Subtractive manufacturing:
  - CNC machining (milling, turning, boring, etc.)
  - Laser cutting
  - Water jet cutting

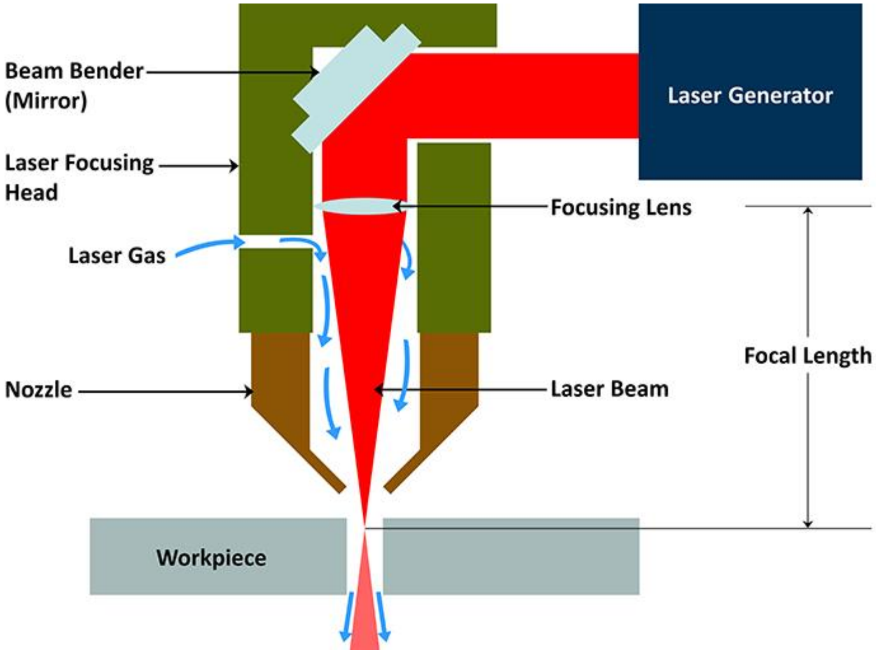
  We will discuss these
- These are powerful tools for prototypes generation
- A little clever design goes a long way





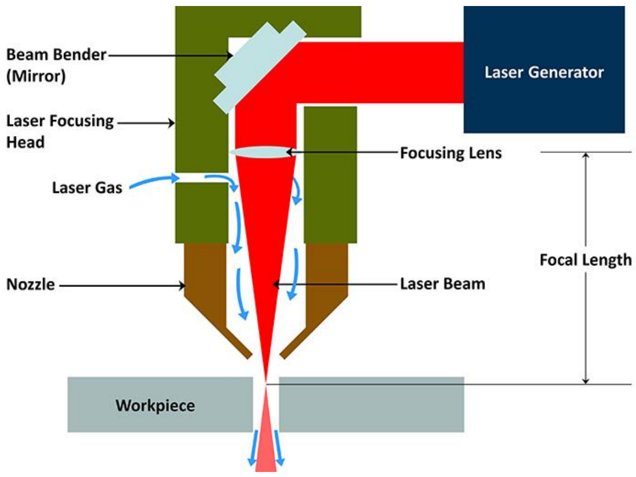
Laser Cutters

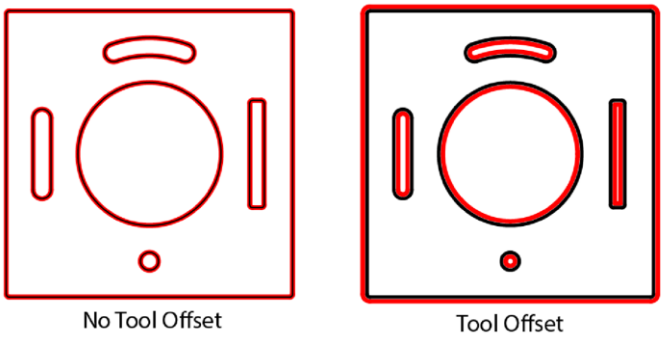
- A laser cutter focuses a laser onto the surface of a part
- Can cut detailed parts as well as raster images (2D)
- Protective gas layer
- The cut has some slight width due to the laser
- Known as "kerf"
- Three types of laser cutters
  - **CO_2 lasers** – tubes containing specialized gas produce a laser that is focused on the part. Power ranges from 25 – 100 W. Cuts most organics, some plastics, and some thin metals
  - **Fiber lasers** – Solid state laser enabling a small focal diameter. Up to 100x more powerful than CO_2 lasers, and versatile, being able to cut metal.
  - **Nd:YAG / Nd:YVO lasers** – powerful lasers with a narrow focal length used to cut many materials, even some ceramics



Kerf and Tool Paths

- Kerf
  - Typically 0.08 – 0.45 mm
  - Depends on:
    - Laser optics and focusing
    - Material type / thickness
- Consequences
  - Parts will be undersized
  - Holes will be oversized
- Tool paths can be offset to account for kerf
- Universal CO_2 laser does not offset kerf
- You will need to modify the parts / .DXF file to account for any tolerances needed





Acrylic

- We will use acrylic
- Also known as Plexiglass, Lucite, Perspex, etc.
- Manufacturing methods
  - Cast – better for laser cutting
  - Extruded – better for thermoforming
- We are using 3/16" acrylic sheets
- Do not cut polycarbonate / Lexan – absorbs IR radiation
  - It looks like acrylic!
- Other materials that **cannot** be cut with a laser cutter
  - PVC, Styrofoam, MDF, glass, metals, chlorinated / nitrile rubbers
- Other materials that **can** be cut with a laser cutter
  - Acrylic, paper / cardstock, hardwood, laser-grade plywood, leather

FRB Makerspace – Laser Cutter

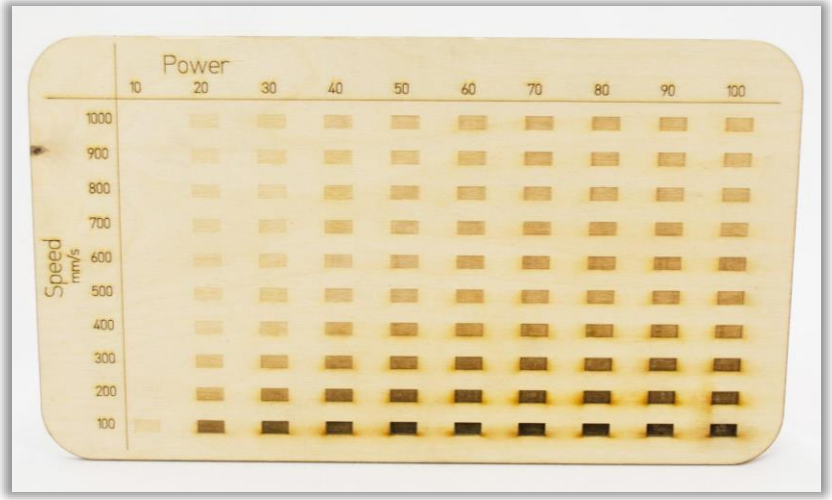
- Laser cutter in FRB Makerspace
- CO_2 Laser
- Universal PLS 75 W
- See instructional information / SOPs uploaded to Canvas
- Laser cutters can be dangerous!
- Follow all safety procedures
- You will need to learn the SOP
- Settings
  - **Power** – intensity of the laser
  - **Speed** – cutting speed
  - **PPI** – laser pulses for rastering
  - **Z-axis** – always set to off

Program to operate CO2 laser

Settings

Vector and Raster Settings

- Vector graphics – graphics that can be scaled. Functions represent the relationships between the pixels, rather than pixel-level data
- Raster graphics – individual pixels (e.g. bitmaps) that encode images. Raster graphics are not scalable
- Line colors
  - Vector cutting – red line
  - Vector etching – black line
  - Raster etching – black filled area
- Other colors are user definable
- Setting the colors can be used to create intricate parts with high detail
- Sometimes test parts are used to verify laser settings



Vector and Raster Settings

- Materials and settings for Universal CO_2 laser
- These are a guide and should be verified with Alyssa / test parts

ACRYLIC	POWER	SPEED	PPI	PASSES	DEPTH
LIGHT RASTER ENGRAVE	22	100	500	1	.002″
DEEP RASTER ENGRAVE	100	90	500	1	.010″
VECTOR ENGRAVE	2	4	1000	1	.005″
VECTOR CUT	100	2	1000	1	.25″

ANODIZED ALUMINUM	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	30	100	500	1	.001″
VECTOR ENGRAVING	4	4	1000	1	.001″

CORK	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	80	90	500	1	.01″
VECTOR ENGRAVING	4	4	500	1	.01″
VECTOR CUT	25	1.6	500	1	.060″

GLASS	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	100	30	300	1	.001″
VECTOR ENGRAVING	10	7.9	300	1	.001″

LEATHER	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	19	100	500	1	.001″
VECTOR ENGRAVING	3	4	500	1	.001″
VECTOR CUT	50	4.1	200	1	.1″

LEATHER	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	19	100	500	1	.001″
VECTOR ENGRAVING	3	4	500	1	.001″
VECTOR CUT	50	4.1	200	1	.1″

MARBLE	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	100	82	500	1	.003″
VECTOR ENGRAVING	10	4	500	1	.003″

MATTE BOARD	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	30	80	250	1	.005″
VECTOR ENGRAVING	10	4	250	1	.005″
VECTOR CUT	25	3.2	200	1	.050″

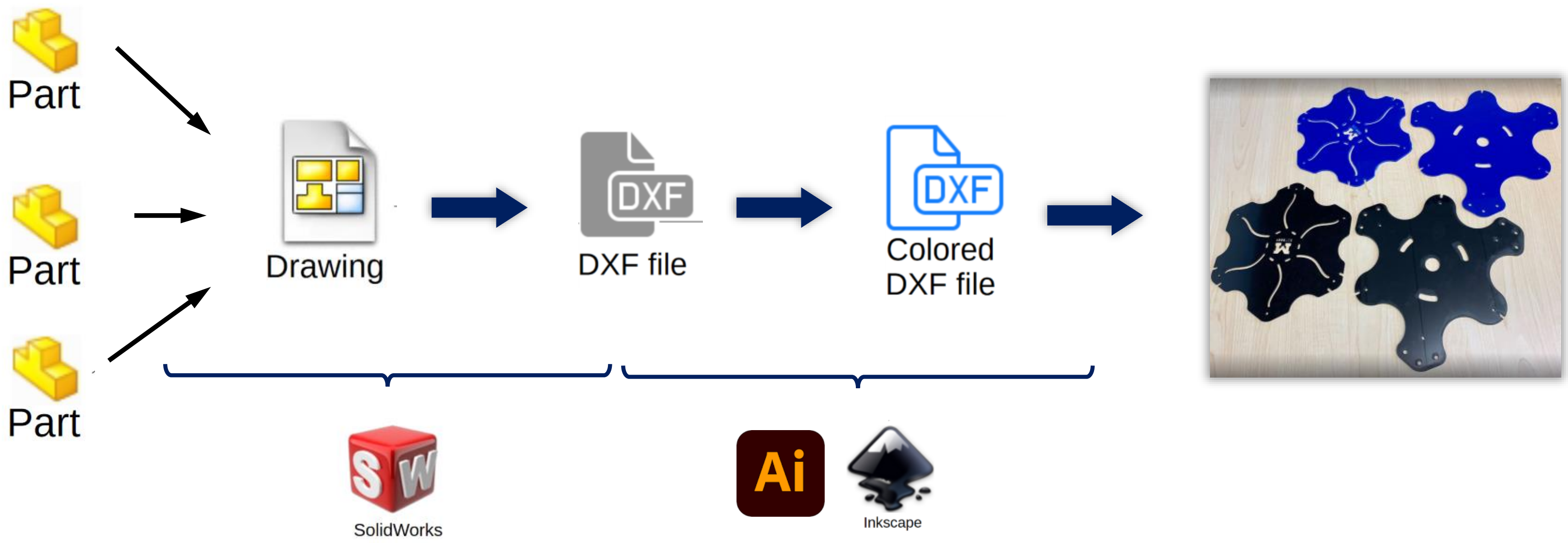
OTHER PLASTICS	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	15	100	500	1	.001″
VECTOR CUT	25	1.2	500	1	.060″

RUBBER STAMPS	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	100	23	500	1	.030″
PERFORATED VECTOR CUT	60	3.1	90	1	.040″

WOOD	POWER	SPEED	PPI	PASSES	DEPTH
RASTER ENGRAVING	100	596	500	1	.020″
VECTOR ENGRAVING	80	10.1	500	1	.030″
VECTOR CUT	50	3.1	500	1	.125″

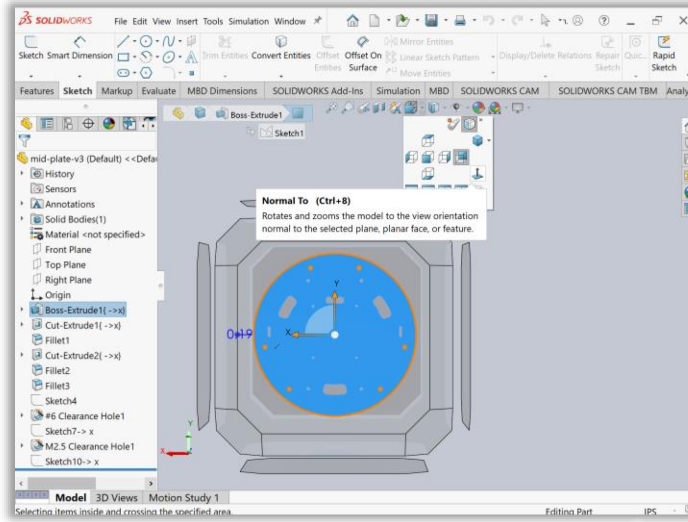
How to Create .DXF Files

- Laser cutters operate in 2D – we need to create 2D files to provide to the laser cutter
- First is to create a drawing in Solidworks
- Then the drawing can be saved as a .DXF file
- Once created, the .DXF file must be altered to provide the correct colors
- The colors of the .DXF provide instructions on the cut type (cut vs. raster)



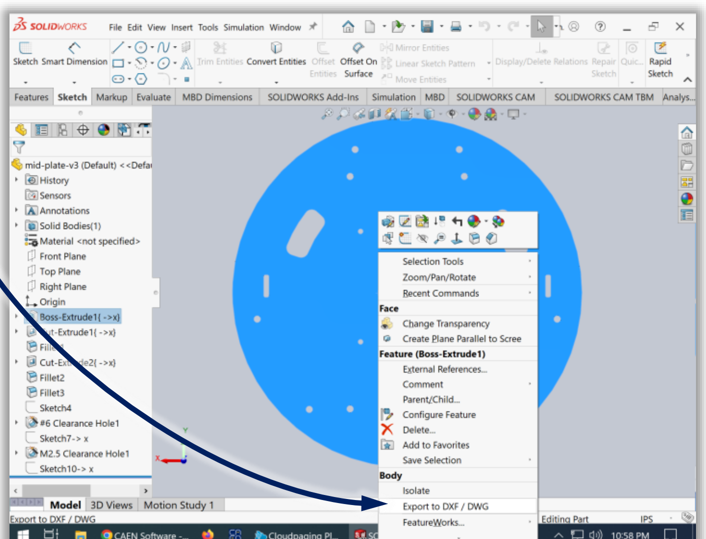
How to Create .DXF Files

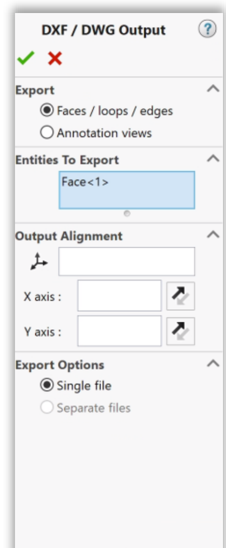
- One easy way is to export directly from Solidworks
- This is especially easy for 2D parts
- To create a .DXF from a 2D part
  - Set part units to “IPS”
  - Select the face to cut
  - Right click and select ‘Export to DXF / DWG’



Set to “IPS”

This exports opens the menu to export a face as a .DXF

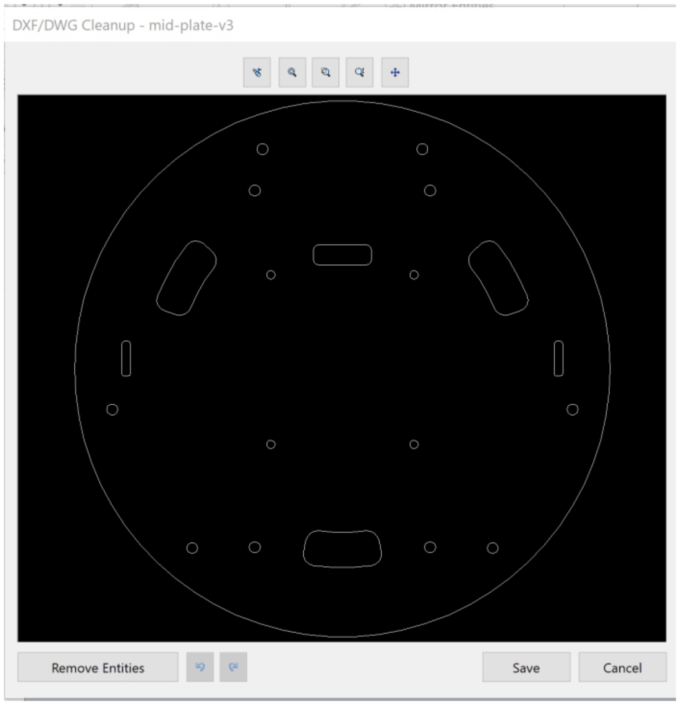




Settings that allow adjustment of export and axis alignment

Changing Colors in Illustrator

- Solidworks allows you to view the .DXF before it is exported
- Adjustments can be made (removal of lines)
- Once the .DXF is created, we need to change the colors
- To tell the laser cutter how to proceed, we need to color the lines in the .DXF file
- Two options:
    - Red: Cut
    - Black: Raster
- Change the colors in Adobe Illustrator or Inkscape
    - Select all then set stroke to red



Set width to 1.5 pt

Set stroke to red