ME370 Design Considerations Lab

ME370 Fall 2025

Table of contents

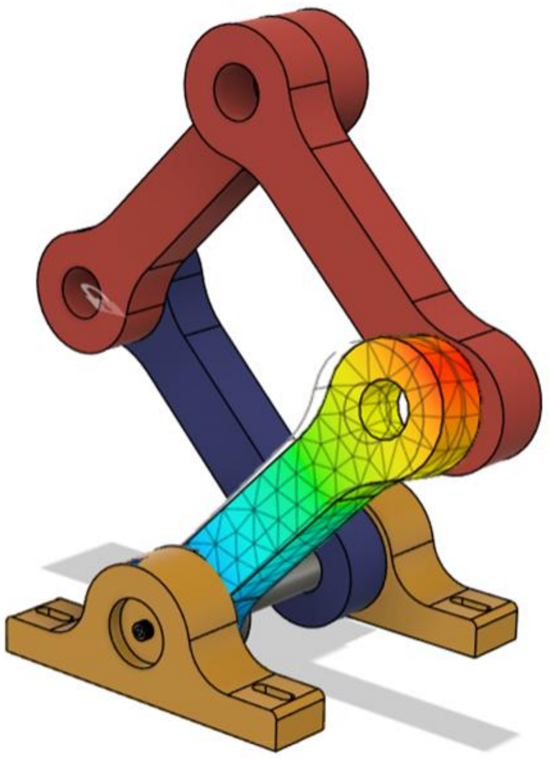
Design considerations

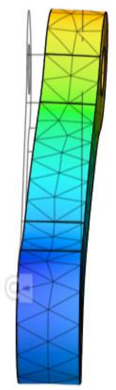
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Design for Strength vs Design for Stiffness

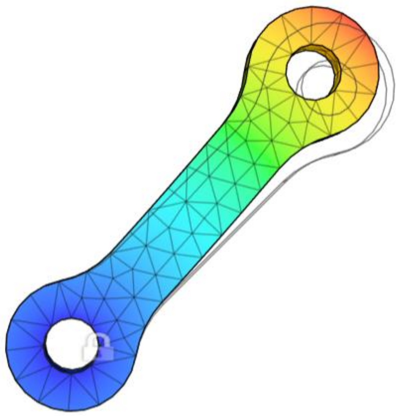
- Machines often fail from **flexibility**, not fracture
- **Deflection** limits precision, alignment, control
- **Stiffness** enables performance — strength ensures survival
- **Modal analysis** reveals weak, flexible directions
- **Low modes** → compliant geometry, vibration risk
- **High modes** → rigid, stable structure
- **Design goal:** Use **rigid, well-proportioned geometry** to raise modes and ensure low deflections and dynamic control

Feature	Design for Strength	Design for Stiffness
Key Property	Stress (σ), Strength (σy, σu)	Stiffness (k), Geometry
Primary Equation	$\sigma = F/A$	$\delta = FL^3/3EI$
Objective	Maximize load capacity before yielding	Minimize deformation under service load
Failure Criteria	$\sigma \leq \sigma allowable$	$\delta \leq \delta max\ allowable$ $F_n < Operational\ Freq.$
When to Prioritize	Safety-critical parts, overload conditions	Precision, vibration-sensitive, alignment-critical systems
Examples	Lifting hooks, bolts, pressure vessels	Robotic arms, machine tools, optical mounts





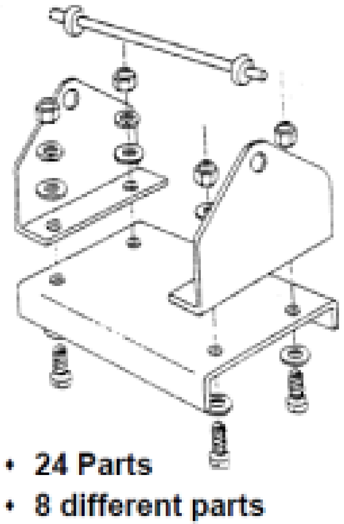
Mode 1. 350 Hz



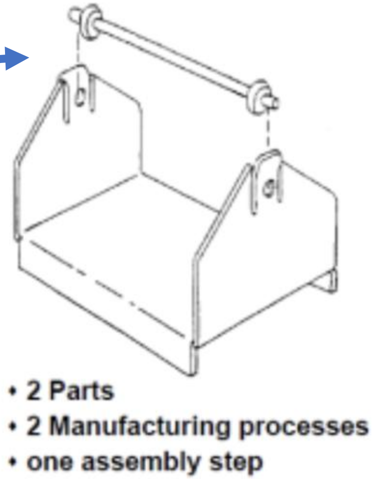
Mode 2. 500 Hz

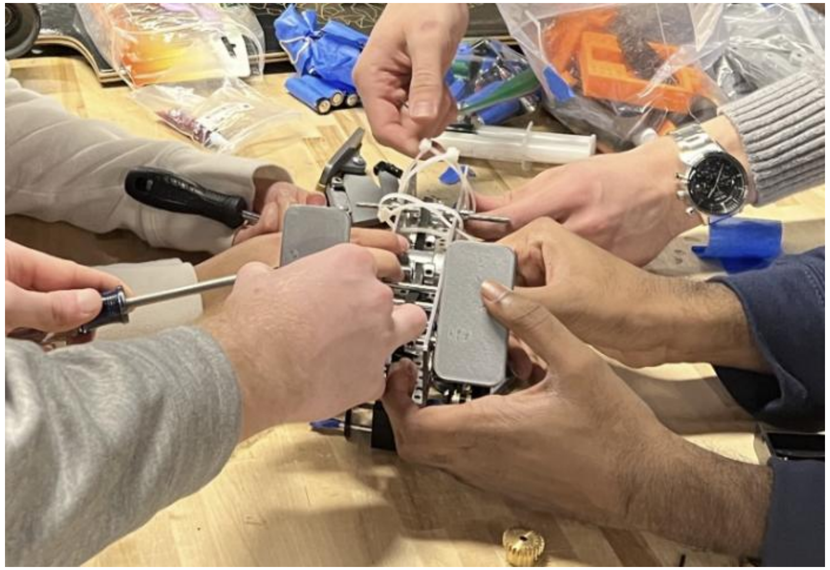
When using CAD think about…

- **Assembly**
  - Some portions of your robot may be more difficult to put together than you think!
  - Consider design chooses to make assembly and disassembly easy.
  - Ask yourself **"Is this physically possible to put together?" / "How long will this take to put together?"**



Same function





- Time Consuming to Assemble
- Hard to troubleshoot ☹

- Easy to assemble
- Easy to troubleshoot ☺

When using CAD think about…

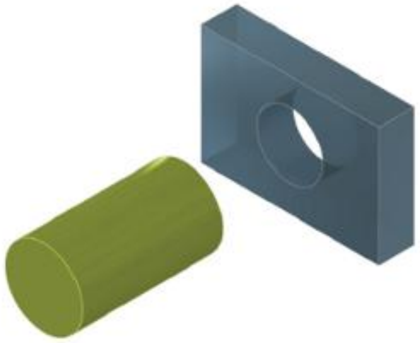
- **Tolerancing**

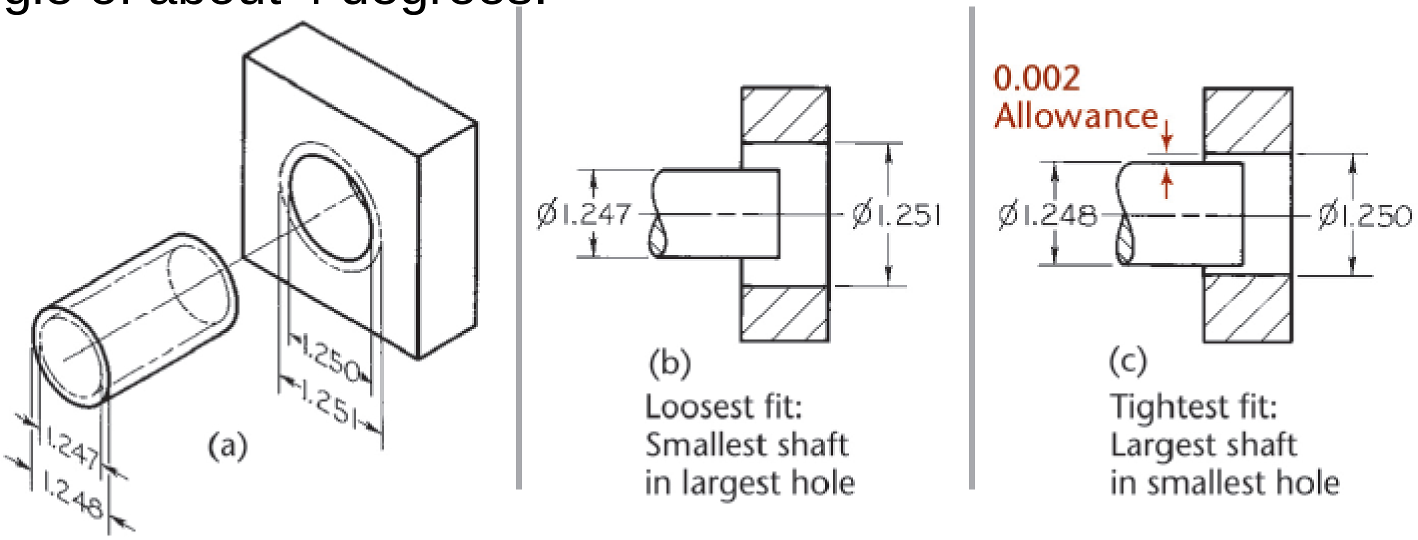
When a shaft/pin is inserted into a hole, the fit between them is determined by their limit dimensions.

A good starting point for 3D printed parts is to increase internal features by 0.2mm

- May work on one printer but may be different on another printer

Laser cut parts often have a draft angle of about 4 degrees.





Shaft tolerance = 1.248 – 1.247 = 0.001

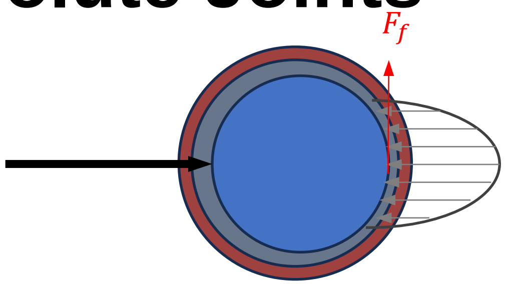
Hole tolerance = 1.251 – 1.250 = 0.001

Allowance = 1.250 – 1.248 = 0.002

Max clearance = 1.251 – 1.247 = 0.004

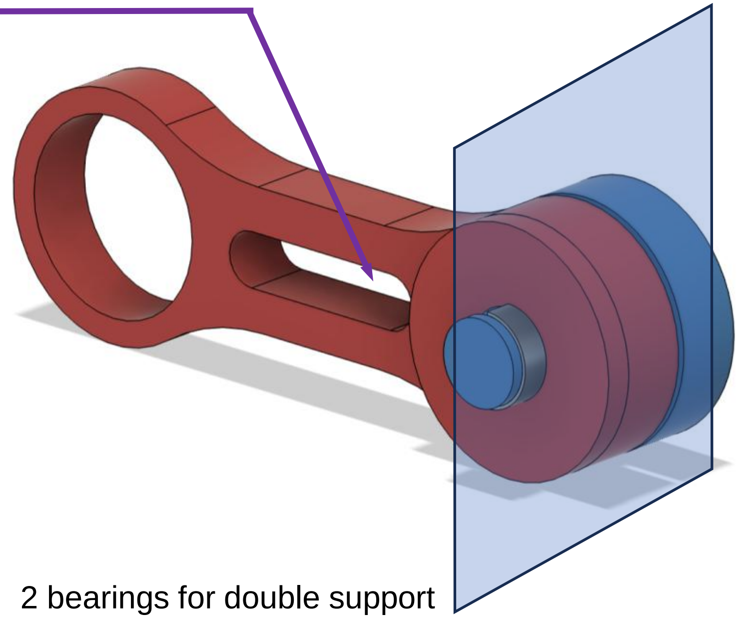
Joints

Revolute Joints

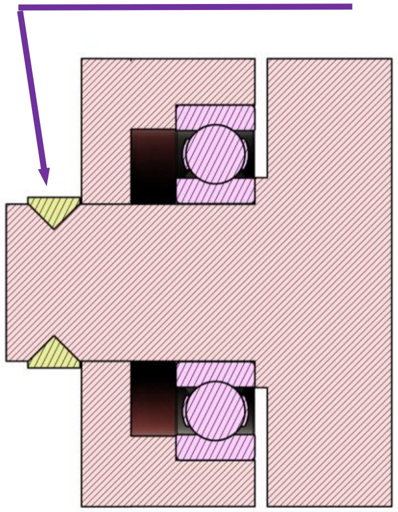


Joints made from high-friction materials (like plastic) generate resistance. Use longer pins (thicker links) with a larger radius to maximize contact area, reduce pressure (and friction), and improve smoothness.

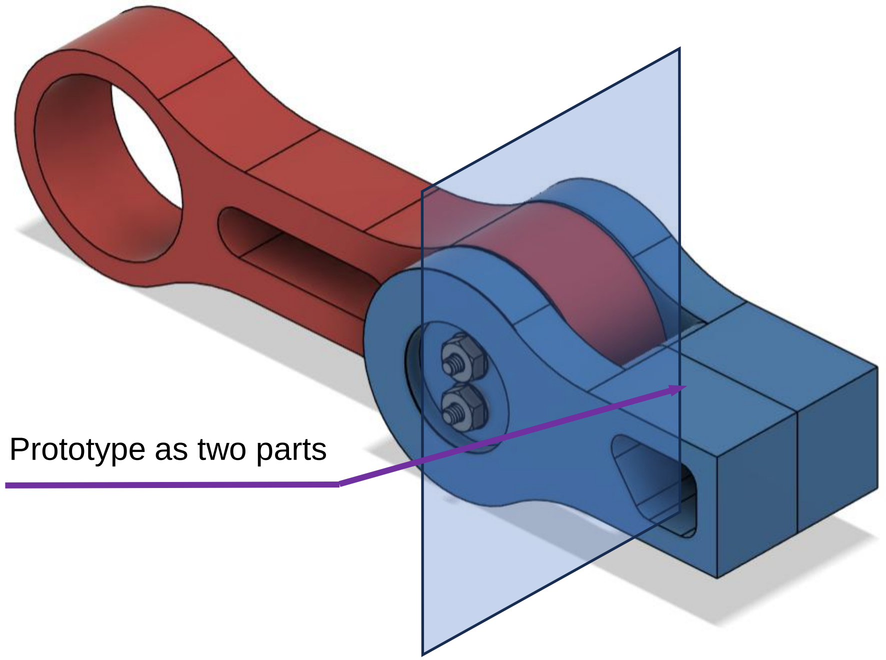
Reduce mass without compromising rigidity. (Laser cut only)



Use retaining ring.

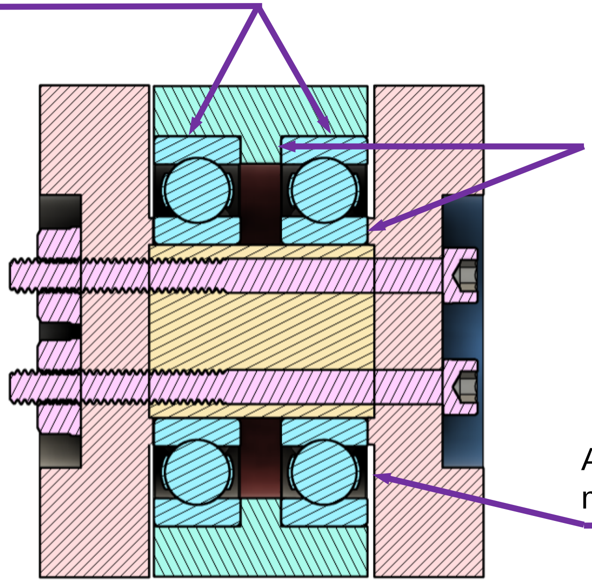


Single shear Joint



Prototype as two parts

2 bearings for double support



Add mating surfaces that support the bearing on both sides to prevent locking.

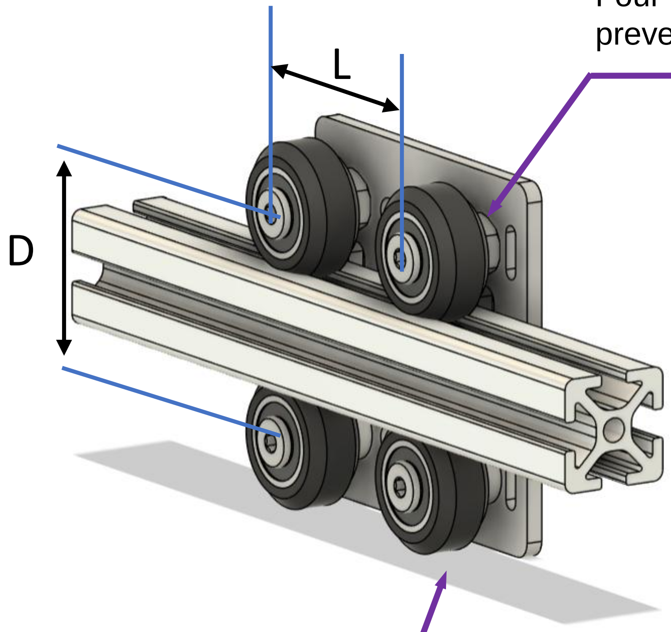
Use knuckle Joints whenever possible

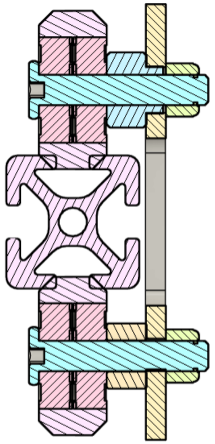
Allow gaps for relative motion

Double shear Joint (Knuckle Joint)

Slider Joints

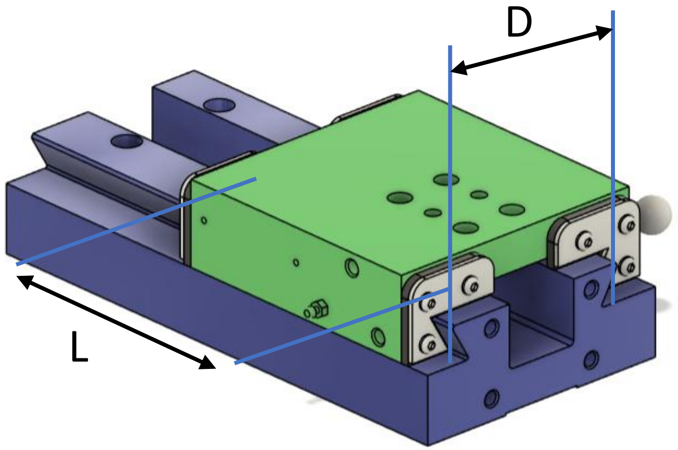
Four rollers work well to prevent undesired rotations.



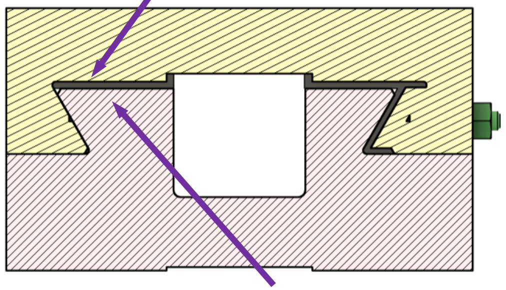


Off-the-shelf assembly

V-slot gantry joints are robust prototyping joints that provide very smooth motion. In any sliding joint, it is important to consider

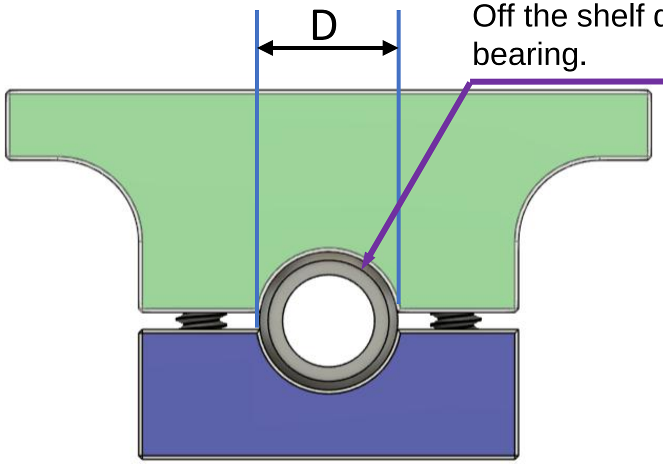


Properly tolerance the bearing surfaces.



Dovetail geometries are self-aligning.

Off the shelf dry running sleeve bearing.



the support ratio (L/D). For smooth and stable operation, this ratio should be greater than 1.5.

Elements

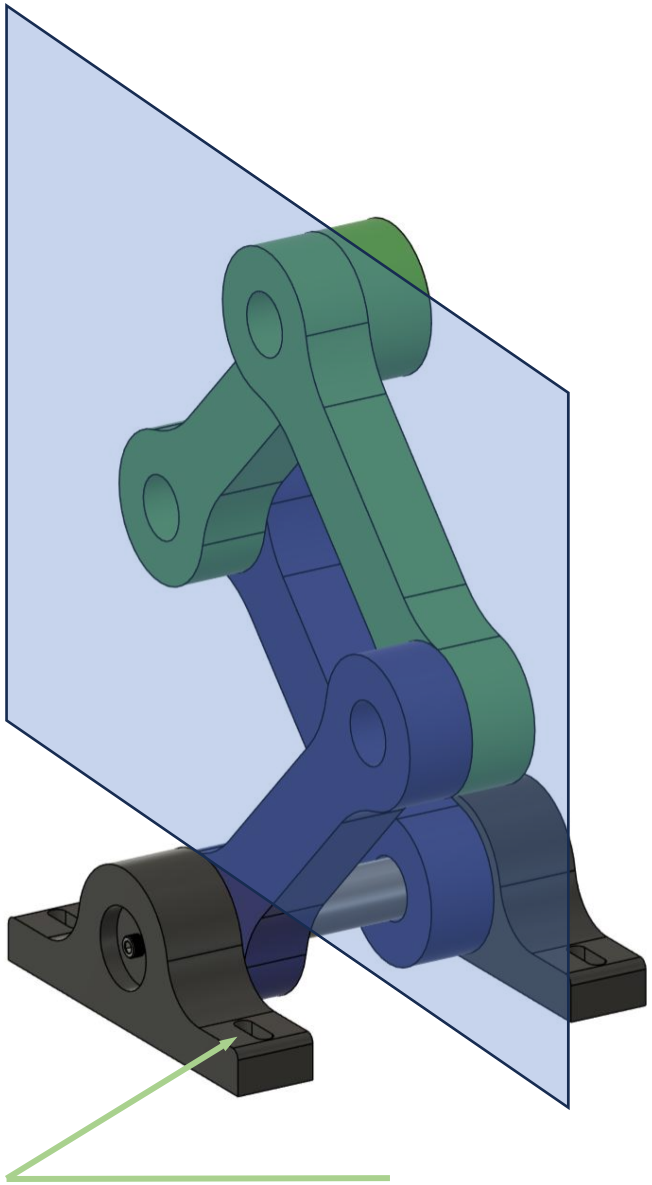
Sleeve Bearings

Sleeve Bearings – makes things run smooth. Can account for friction against plastic + shaft

Ball Bearings

Ball Bearings – makes things run smooth. Can account for friction against plastic + shaft (generally more durable and have better longevity than sleeve bearings)
*Not available at Innovation Studio; Mostly used during ME371

Linkages

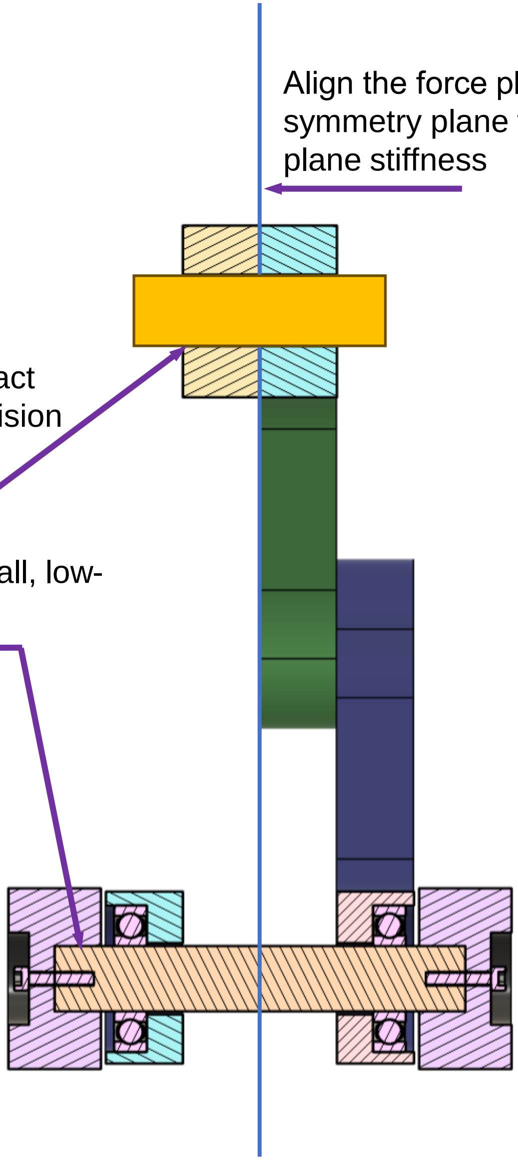


Use alignment slots instead of holes to allow prototype adjustability.

Align the force plane with the link's symmetry plane to maximize out-of-plane stiffness

Surface-to-surface contact can be used in low-precision prototypes.

Glue can be used in small, low-force prototypes.



Gears

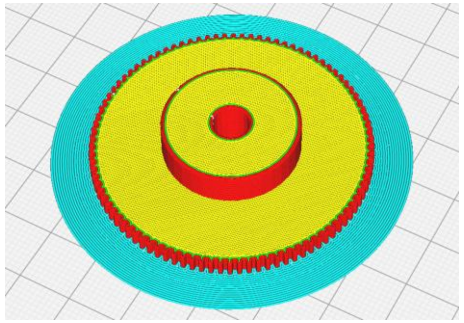
BAD GEAR DESIGN
(For 3D Printing / Acrylic Laser Cutting)

- Teeth to Size Ratio – Is LARGE:SMALL
- Keep in mind of the capabilities of the innovation studio printers

96 Teeth – 2in

Too many teeth for a small gear – will not mesh well.

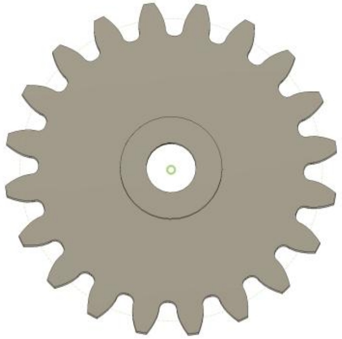
Failure to Tolerance Shaft hole adequately.
Gear will not fit your shaft (hole is too big)



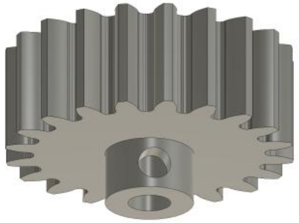
Adding a brim .
Gear teeth will be jagged at one end of the gear and will not mesh well at that point of contact (especially true for thin gears)

GOOD GEAR DESIGN

- Chamfer bottom edge to get clean profile if 3D printing
- Use larger teeth

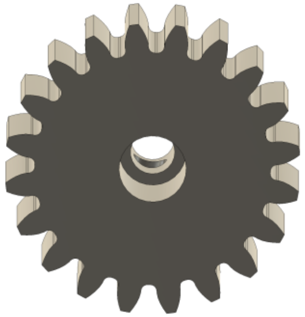


20 Teeth – 40mm



Adding a Shaft Collar

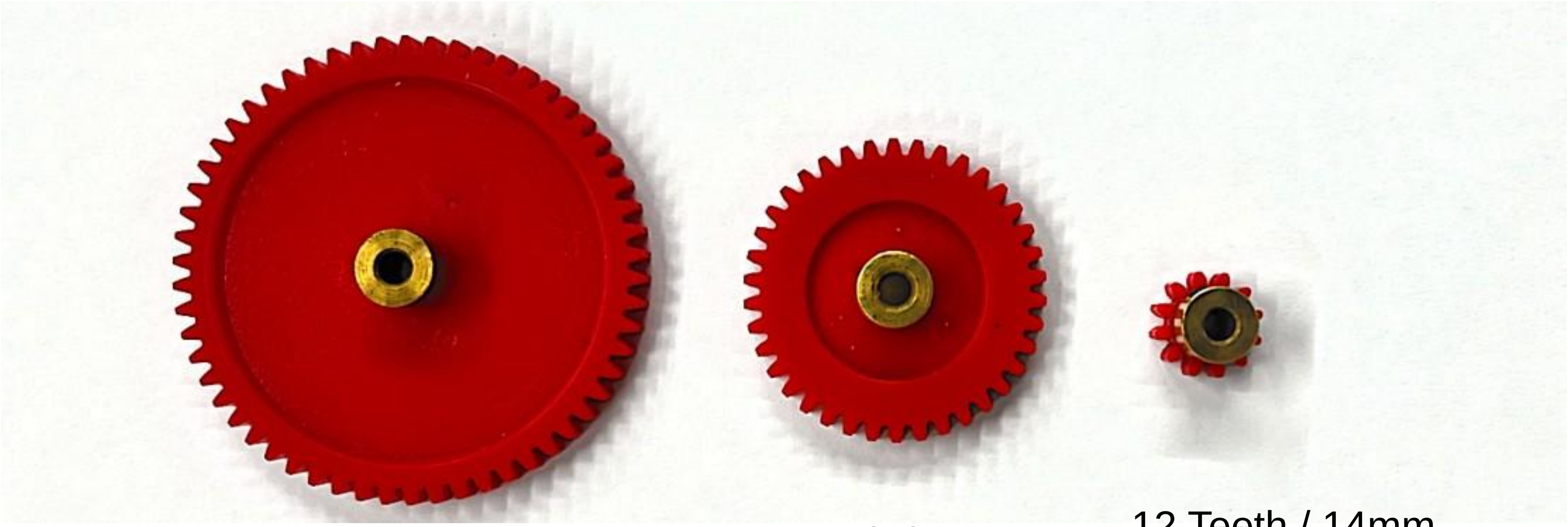
Considering mounting..
(shaft collar included on gear)



Bearings!

Adding enough space for a bearing!

We also have a limited stock of Red Gears



58 Teeth / 60mm
Outer Diameter

https://www.railwayscenics.com/plastic-tooth-58mm-gear-with-brass-p-804.html

38 Teeth / 38mm
Outer Diameter

12 Teeth / 14mm
Outer Diameter
4mm Brass Hub

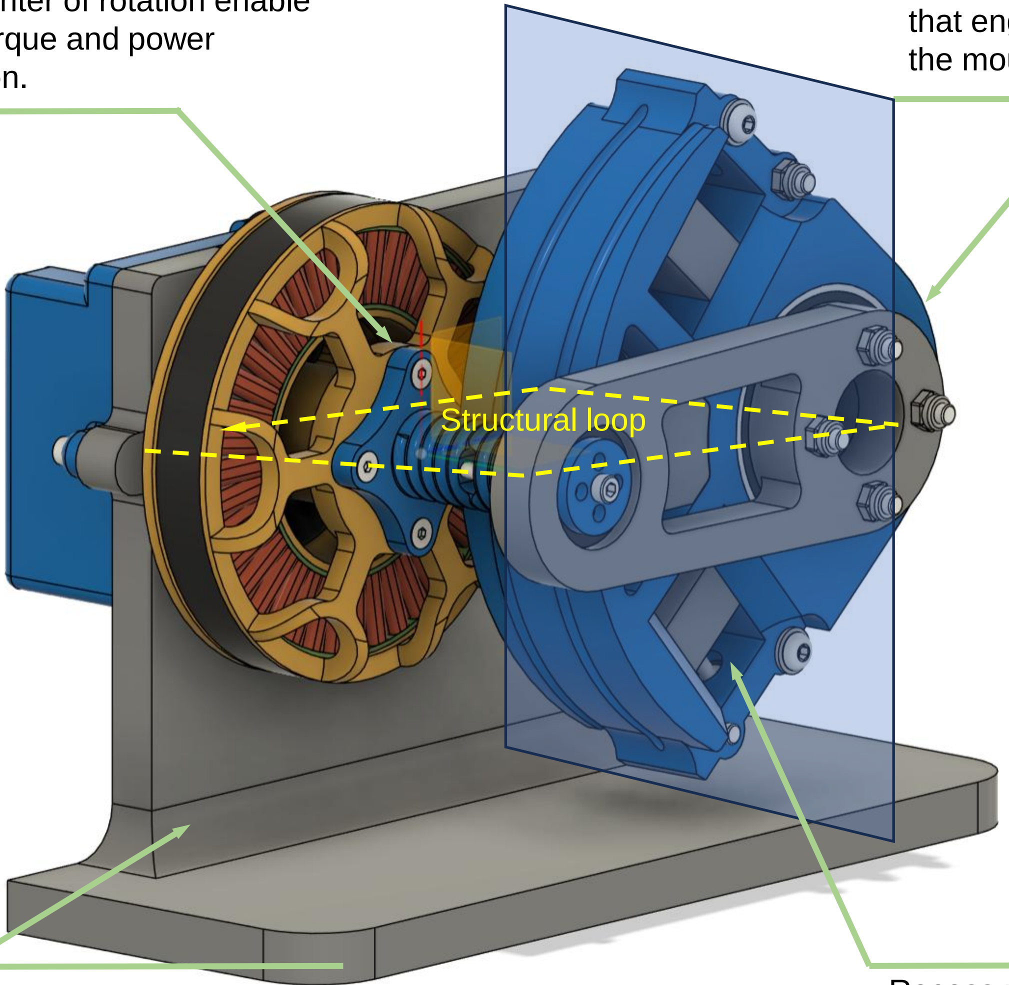
https://railwayscenics.com/plastic-tooth-12mm-gear-with-brass-p-800.html

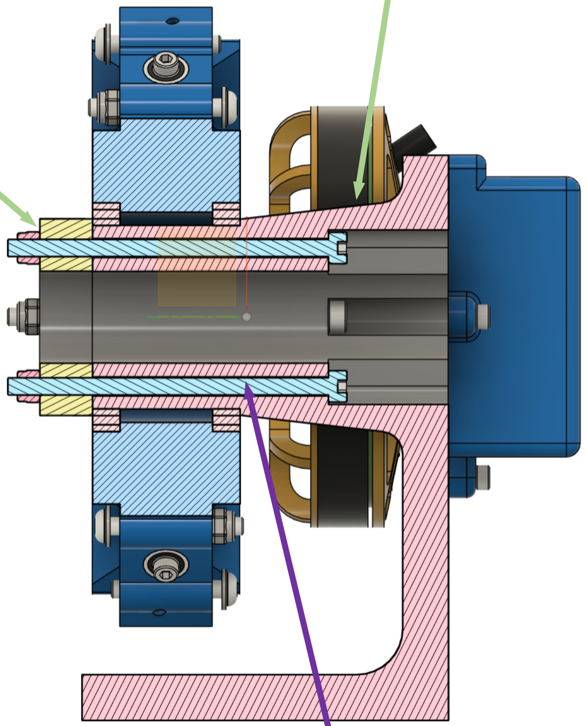
Actuation (Capstan Drive by Aaed Musa)

Multiple attachment points away from the center of rotation enable effective torque and power transmission.

When mounting the motor from the side, create structural loops or brackets that engage elements on both sides of the mounting face.

Tapered cantilevered element to increase stiffness.





Use hollow parts and metallic inserts to reduce mass and improve rigidity.

Fillet sharp corners to avoid deflections and stress concentrators.

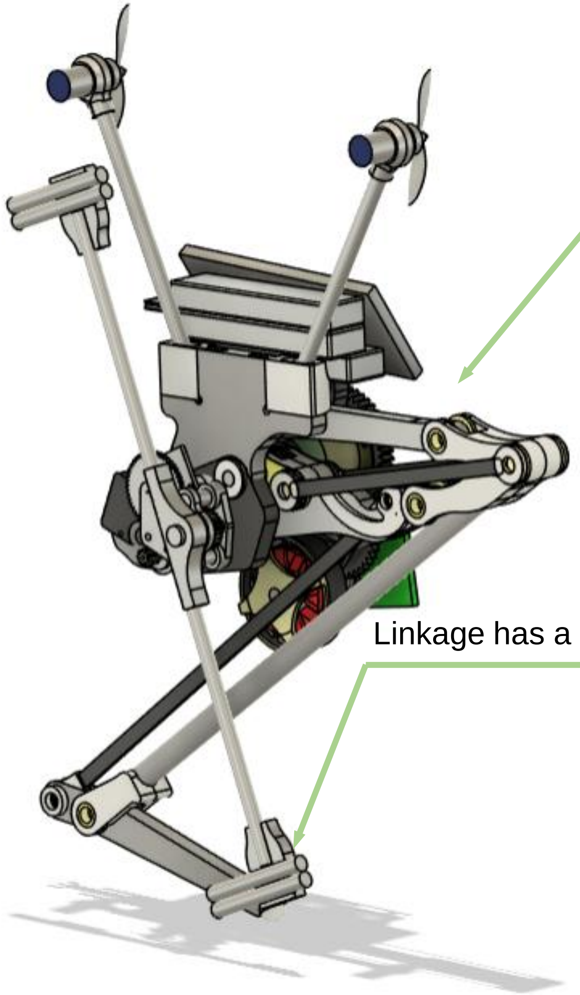
Recess material in low strain energy regions to reduce mass without compromising rigidity.

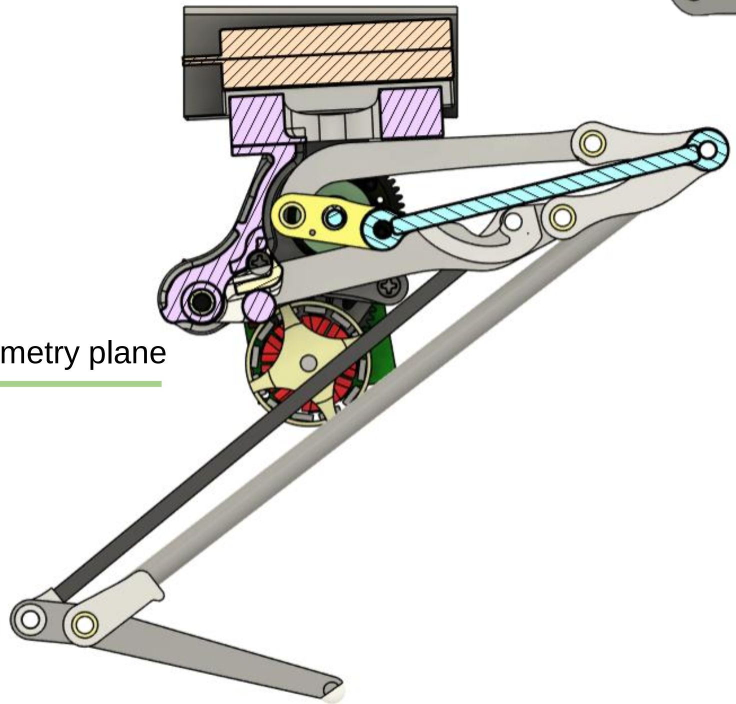
[Capstan Drive by Aaed Musa]

Machine

Frame and Mechanism consideration (Salto)

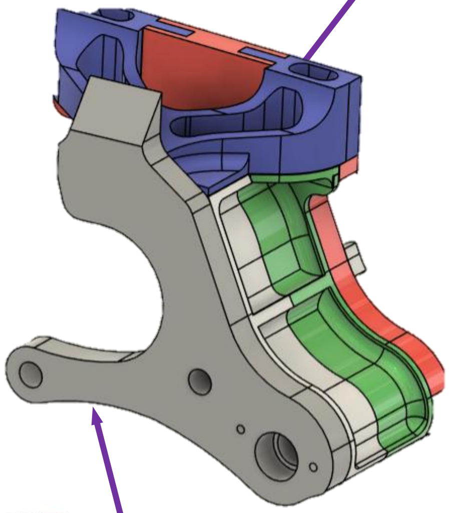
Salto –by Duncan W. Haldane, M. M. Plecnik, J. K. Yim, and R. S. Fearing*, a jumping robot, is a great example of mechanism integration and craftsmanship.

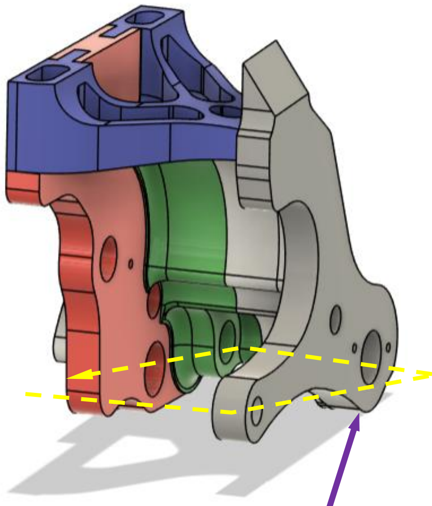




Knuckle joints.

Linkage has a symmetry plane





Use hollow parts to reduce mass and maintain rigidity if metal.

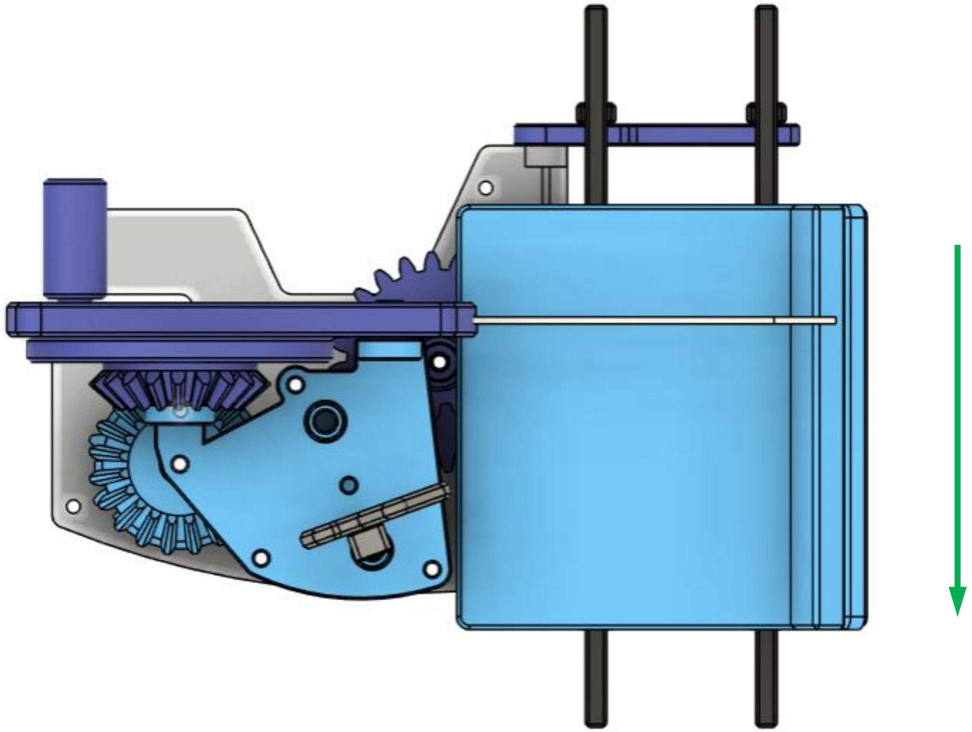
A structural loop that supports the motor and gearbox from both ends.

The chassis can be manufactured using 2D or 2.5D processes (with better material properties), such as laser cutting, and assembled into functional 3D parts.

[Robotic vertical jumping agility via series-elastic power modulation]

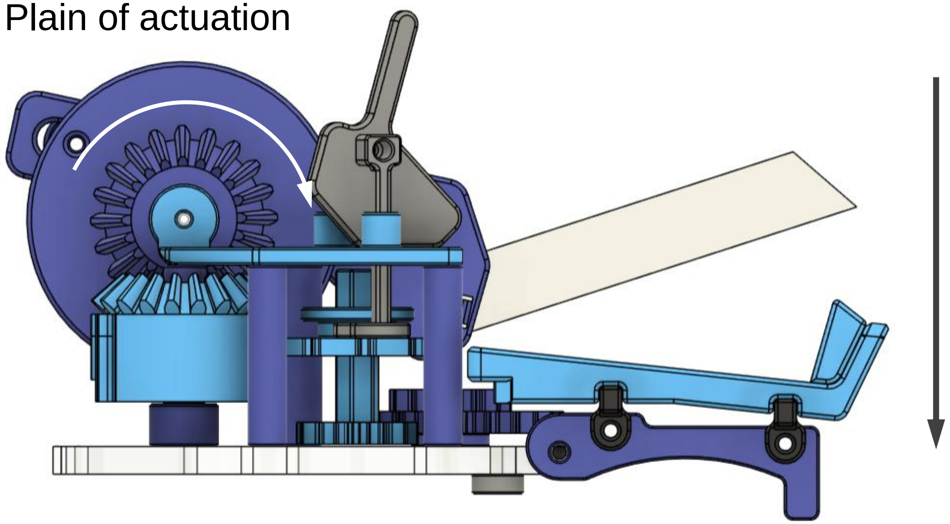
Machine Considerations

- Align actuation with the primary direction of work
- Use bevel gears to change motion direction or transmit power over distance with shafts
- Implement dwelling mechanisms (e.g., Geneva wheels, intermittent gears, cams) to program transitions between functionalities
- Maintain structural distinction between the chassis, mechanisms, and enclosure



Secondary direction of work (feeding)

Plain of actuation



Primary direction of work (cutting)

Fasteners

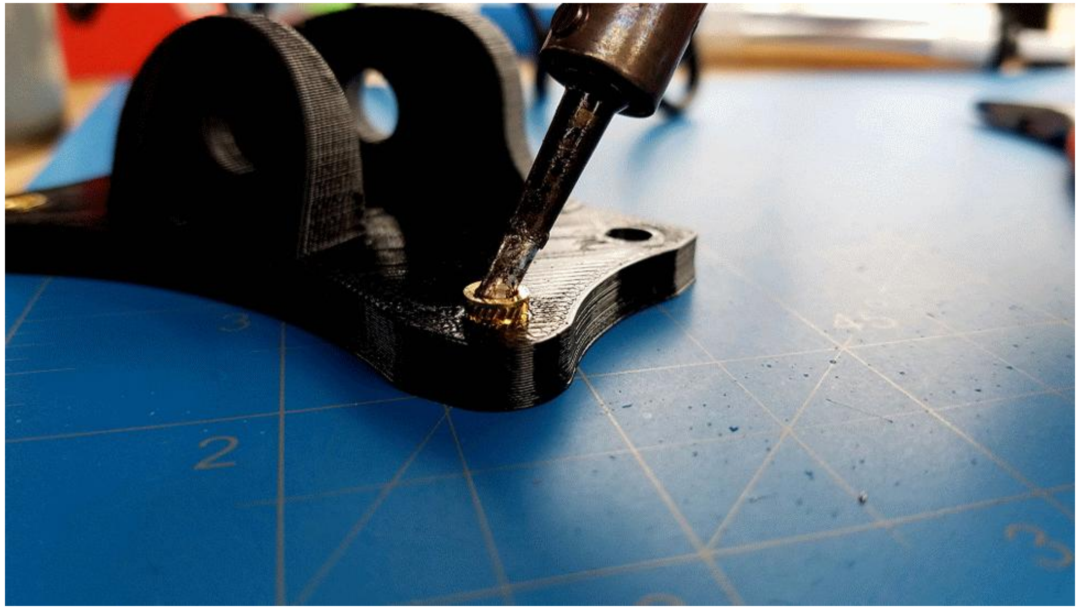
Fasteners- Threaded Heat Set Inserts

For anything you design that needs to be screwed together, consider adding a threaded heat set insert!

- Plastic over time will wear down each time you unscrew and screw.
- Threaded heat set inserts make that process smoother and more resistant to wear.

How to:

1. Design a hole that is approx. the same size as the insert (larger will have the threaded insert fail)
2. Using a soldering iron to hold the threaded insert, gently place into created hole.

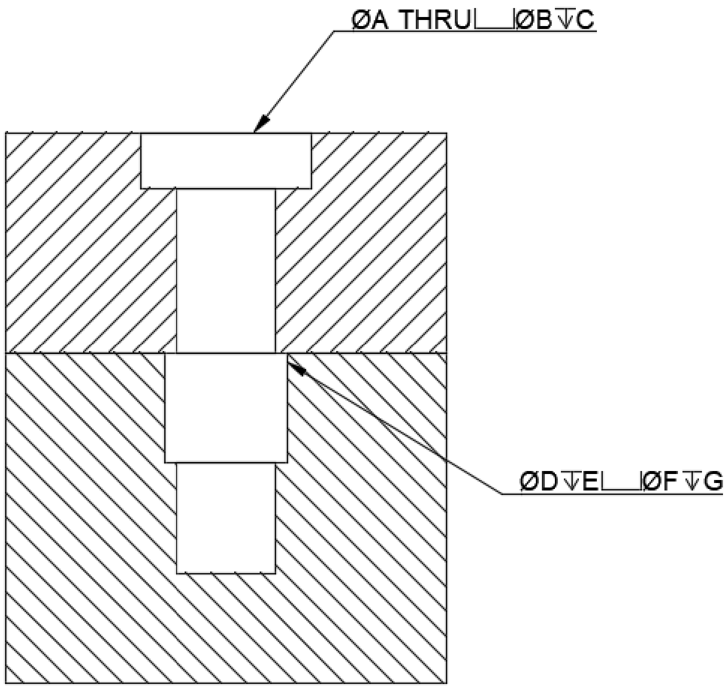


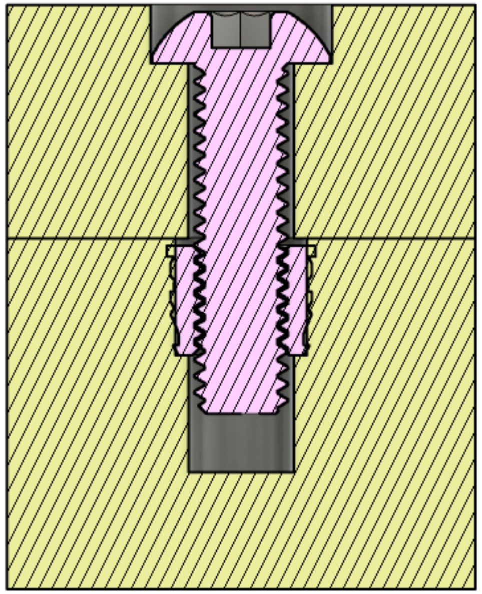
The heating of the insert will allow for the plastic to melt around it and smoothly enter. **DO NOT TOUCH SOLDERING IRON TO PLASTIC.**

https://markforged.com/resources/blog/heat-set-inserts

Fasteners- Designing for Heat Set Inserts

	M3	M4	M5	M6
A [mm]	3.5	4.5	5.5	6.5
B [mm]	6.1	8.0	9.9	10.9
C [mm]	1.9	2.5	3.0	3.5
D [mm]	3.5	4.5	5.5	6.5
E [mm]	*	*	*	*
F [mm]	4.9	5.5	7.6	8.7
G [mm]	4.0	4.9	6.9	7.8





* Dependent on material thickness, leave room for extra screw length to protrude past insert

Fasteners- Shafts , Set Screws and Collars

- Use D-Shafts for this project!
- Mounting gears is possible!
  - Can use Shaft collars or set screws
  - Not so possible on circular shafts

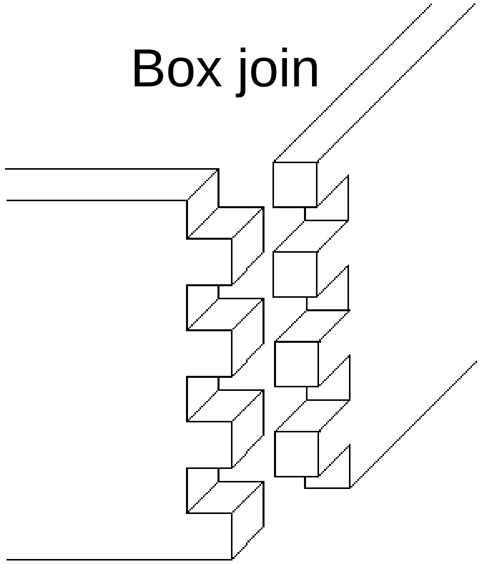
Buy a shaft collar directly (~$1.50)

Can use set screws with a 3d printed shaft collar! (~$0.50)

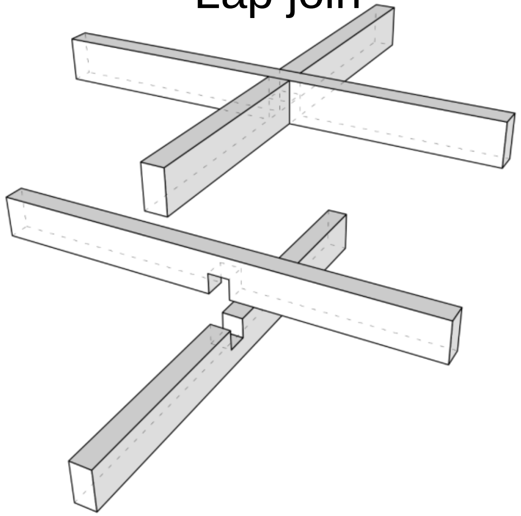
Joinery

- Design holes, slots & grooves into your CAD components
- Highly conducive to laser cutting
- Self aligns components
- Adds mechanical rigidity
- Allows alignment of shaft holes
- Can use screws to hold components together
- Remember to add pilot holes for screws!

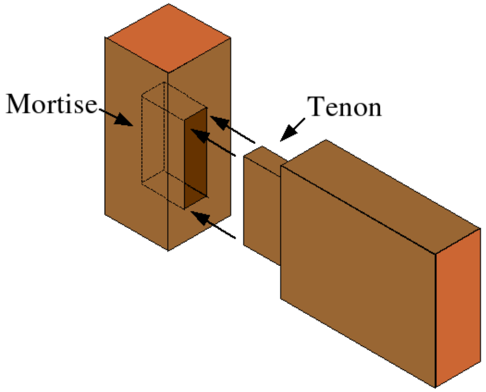
Box join



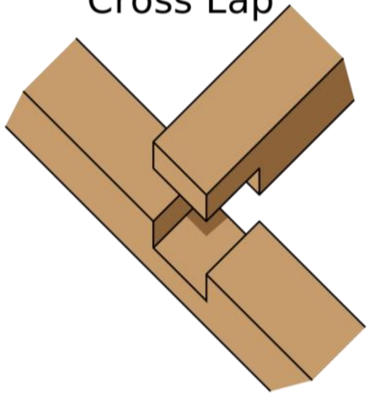
Lap join



Mortise & Tenon



Cross Lap



Manufacturing (prototyping) considerations

Materials

Wood

- Subtractive Manufacturing
- Tolerance holes slightly smaller
- Great for making boxes
- Cheaper than acrylic

Acrylic / Delrin

- Subtractive Manufacturing
- Tolerance holes slightly smaller
- Great for making boxes
- Great for 2d designs (gears)
- $20 per sheet (both cost the same now)

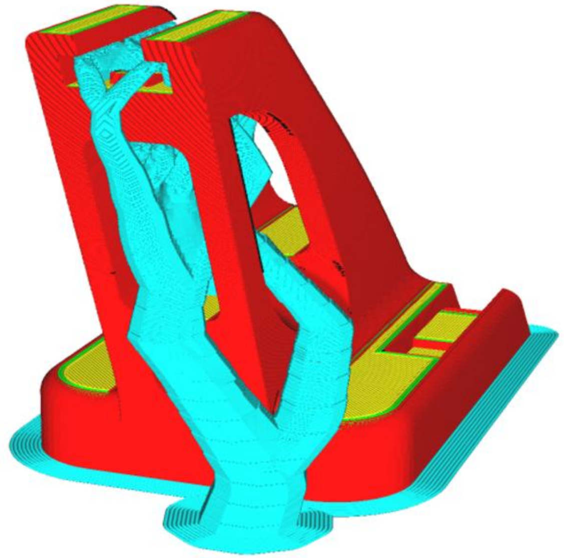
3D Printing

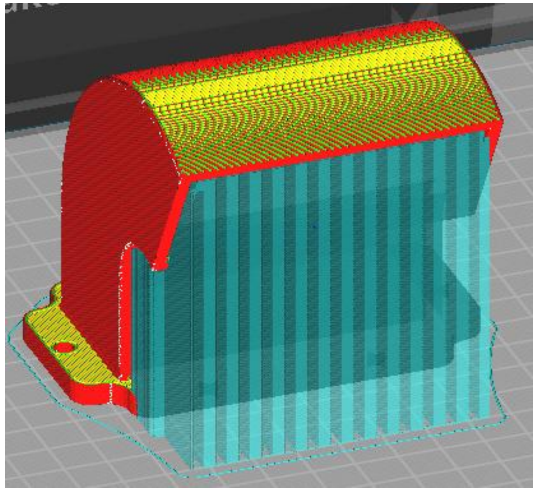
- Additive Manufacturing
- Tolerance holes slightly larger
- Great for intricate designs

Support Structure

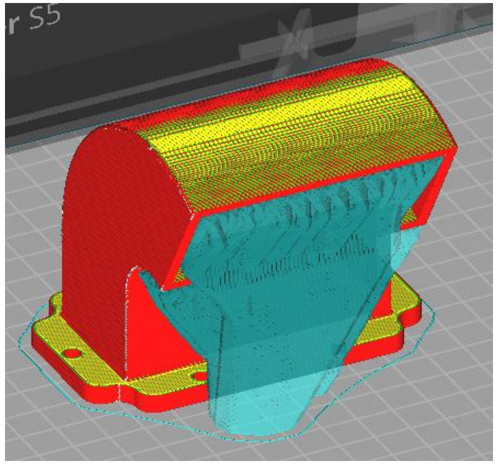
Tree Support Structure

- Depending on complexity of the part tree support structure can be useful
- Easier support removal because of low contact area
- Takes longer to print than linear supports
- Not great at supporting large flat surfaces



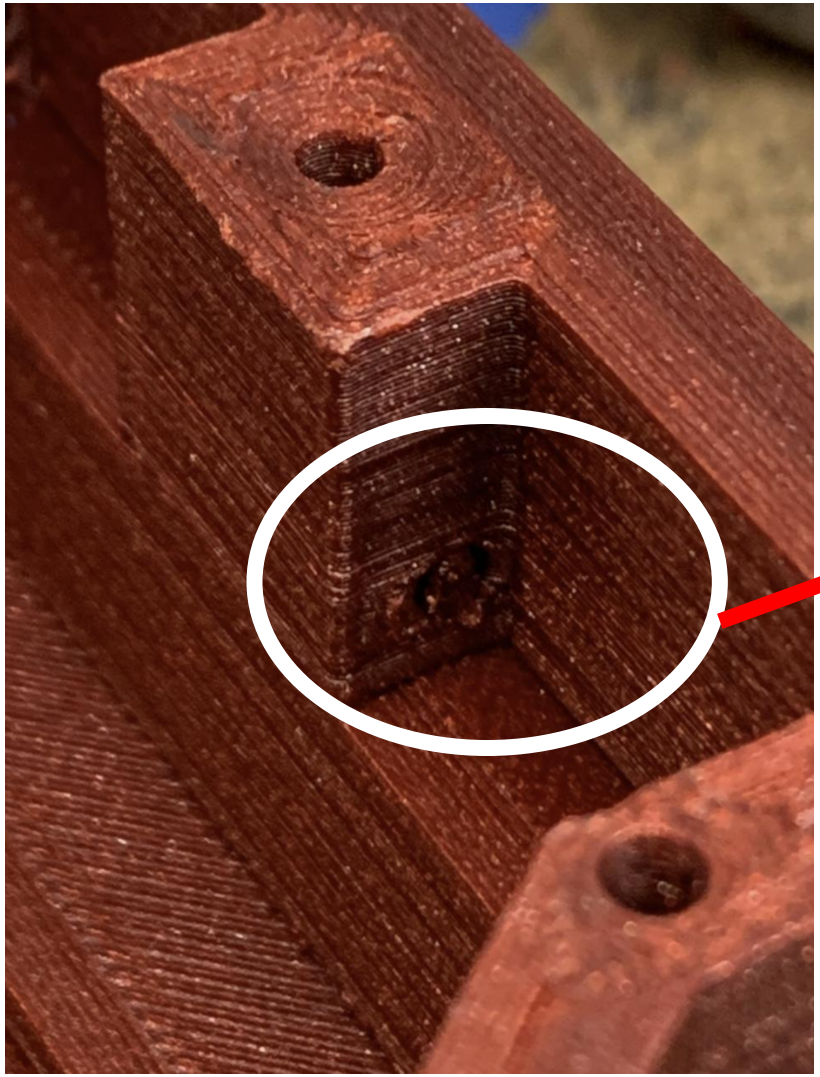


Linear Supports



Tree Supports

Support Structure



<u>Sometimes</u>, it's ok to ignore support structure.

This is a very small hole, and it has support structure in it. In its current configuration it is hard to remove the support structure. As there is surrounding walls.

In this case, ignoring support structure may have been the better option.