Robotics 311 : How to build robots and make them move

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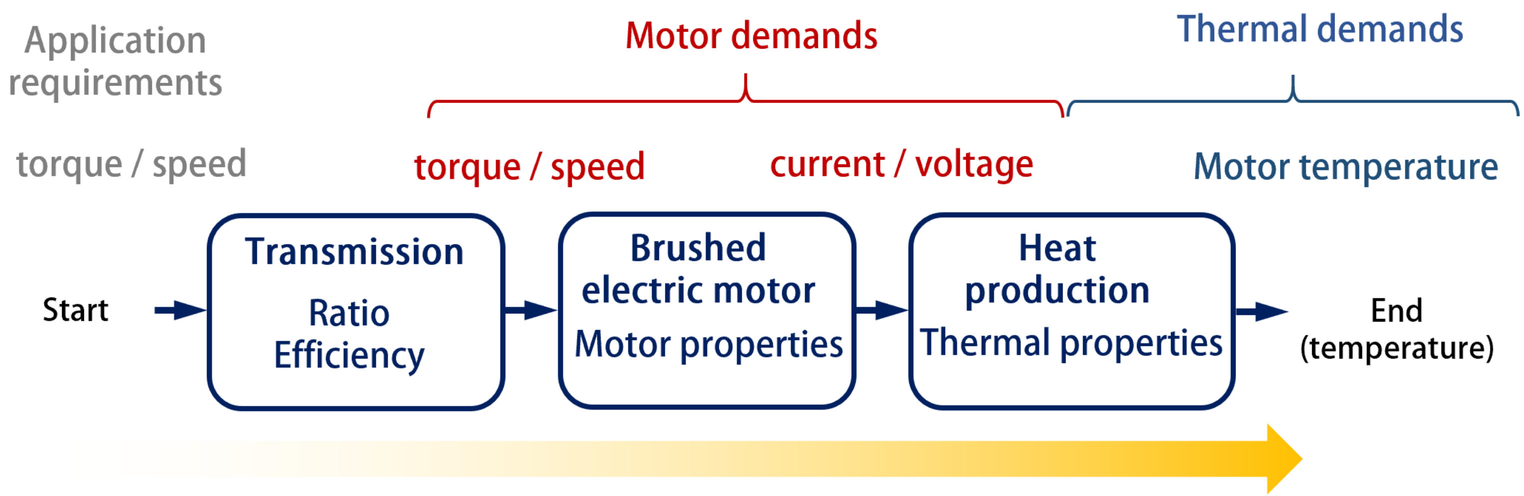
ROB 311 – Lecture 7

- Today:
  - Thermal review
  - Begin ‘making’ section of the coarse
  - Introduce manufacturing
  - Focus on additive manufacturing

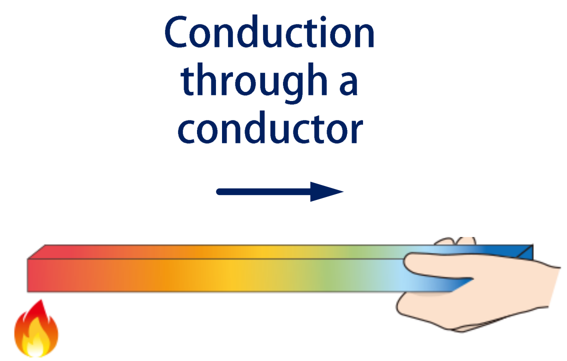
Design Analysis Framework



- Now lets discuss the final step in the analysis framework – prediction of temp
- Where does thermal input come from? - Joule heating from motor windings
- Rules of thumb / metrics exist to shortcut this analysis (e.g. motor continuous current rating, etc.)
- We are learning this because
  - It is relevant to system designs where mass is an important factor
  - They are important concepts for robot designers to be familiar with

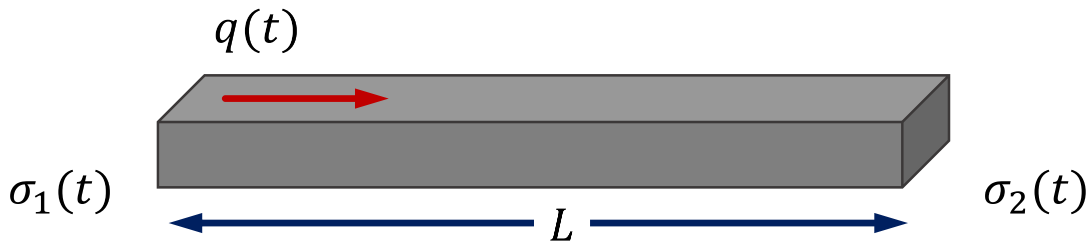
Thermal Modeling

- Crash course in heat transfer modeling
- Heat flows from the motor windings to the housing to the atmosphere
- This includes two types of heat transfer
  - **Conduction** – heat energy exchange between two objects
  - **Convection** – transfer of heat energy between an object and the environment
- Convection and conduction have the same underlying governing equations
- If we understand the equations, we can predict the motor winding temperature
- Lets start with conduction



Thermal Modeling

- Conduction - heat flux $q(t)$ in Watts – comes from $i_w^2 R$ from motor windings



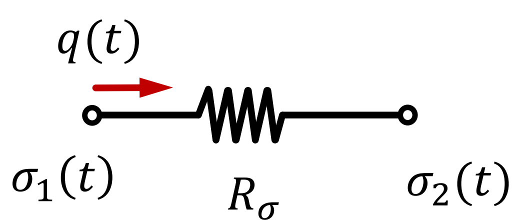
- Thermal resistivity, units K/W is below, using thermal conductivity κ (W/mK)

$$R_\sigma = \frac{L}{A\kappa}$$

- Thus,

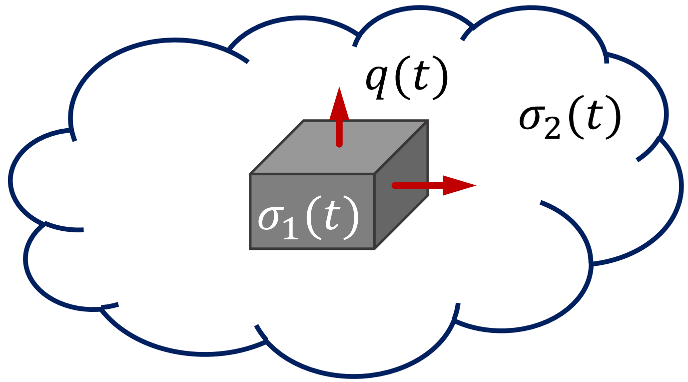
$$q(t) = \frac{\sigma_1(t) - \sigma_2(t)}{R_\sigma}$$

This looks familiar - Thermal version of Ohm's Law



Thermal Modeling

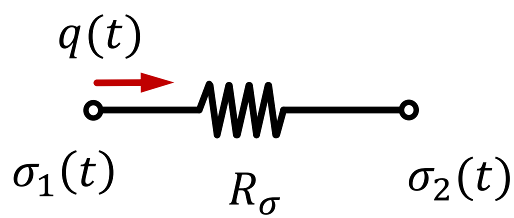
- Convection



- Convection has identical governing equations
- Consider an object in the atmosphere with surface area A and convective heat transfer coefficient h (W/m^{2}C)

$$R_\sigma = \frac{1}{hA}$$

$$q(t) = \frac{\sigma_1(t) \; - \sigma_2(t)}{R_\sigma}$$



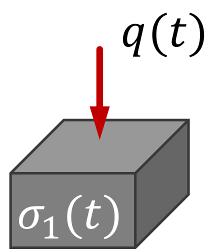
- R_σ can be changed with heat sinks, etc.

Thermal Modeling

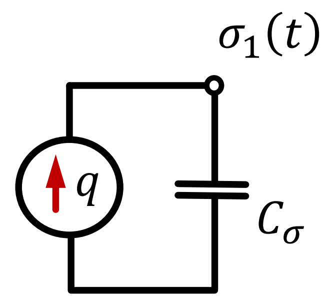
- Thermal capacitance (also called thermal mass)
- Describes an objects ability to store heat energy

$$C_\sigma = mc_p$$

- m is the objects mass and c_p is the specific heat (J/kgK)



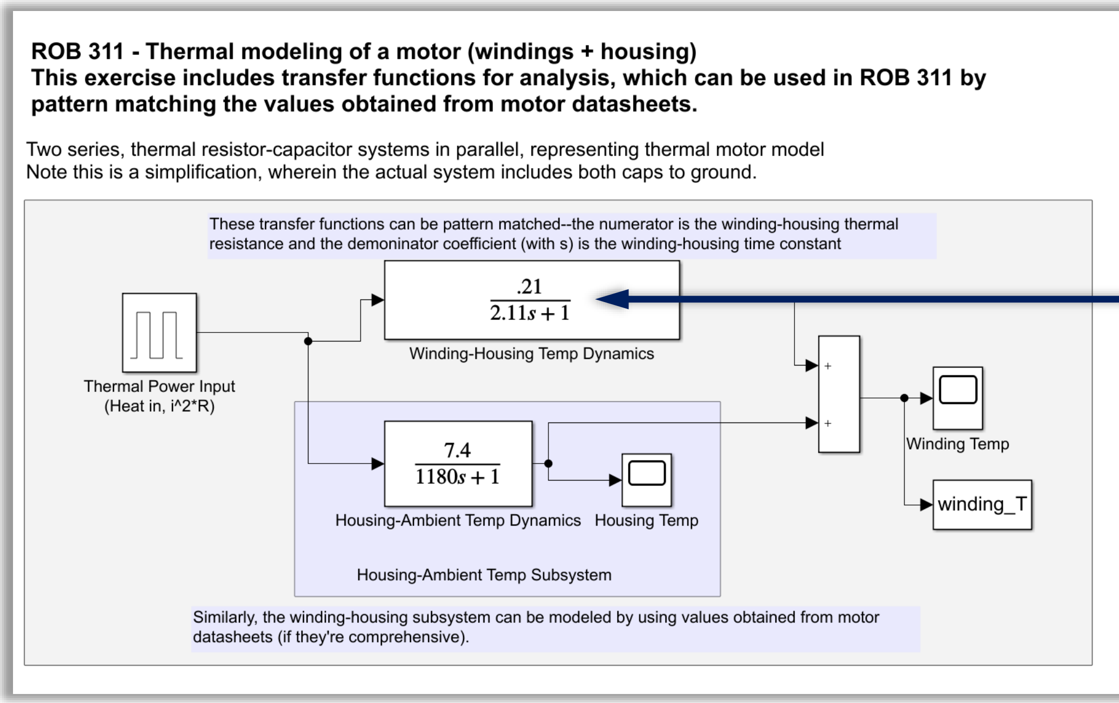
$$q(t) = C_\sigma \frac{d}{dt}\sigma_1(t)$$



- Thermal systems have the same relationships as electrical systems
  - Voltage is analogous to temperature (effort)
  - Current is analogous to heat flux (flow)
  - Resistances and capacitances

Thermal Modeling Example

- These analyses can be completed using Simulink
- I will show a transfer function based modeling solution – feel free to use
- Steady state temperatures can be found using Ohm's Law
- First, lets look at a Simulink example



These are of the form:

$\frac{R_\sigma}{R_\sigma C_\sigma s+1}$ or

$\frac{R_\sigma}{\tau_\sigma s+1}$ where

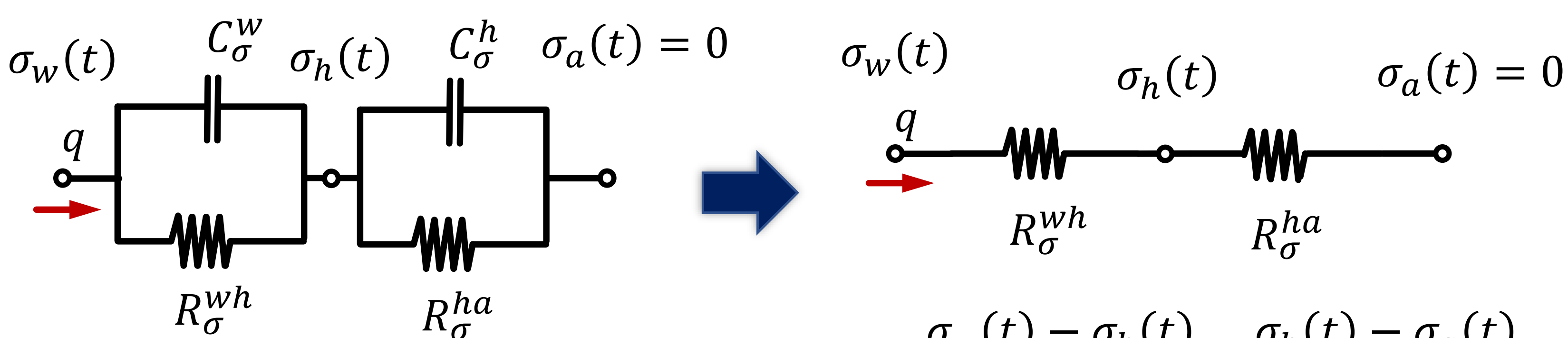
τ_σ is the thermal time constant

Thermal Modeling

- Datasheets often provide the maximum continuous torque / current
- If you use these, your design will always work
- If you want to push the limits, the thermal analysis can be used to design systems that take advantage of the delay / dynamics of the system

5 Nominal torque (max. continuous torque)	mNm	94.6	94.2	92.9	
6 Nominal current (max. continuous current)	A	7.58	5.03	3.68	

- This is based on the forced response (steady state) solution to the thermal ODE
- In steady state, the system behaves like two resistors in series



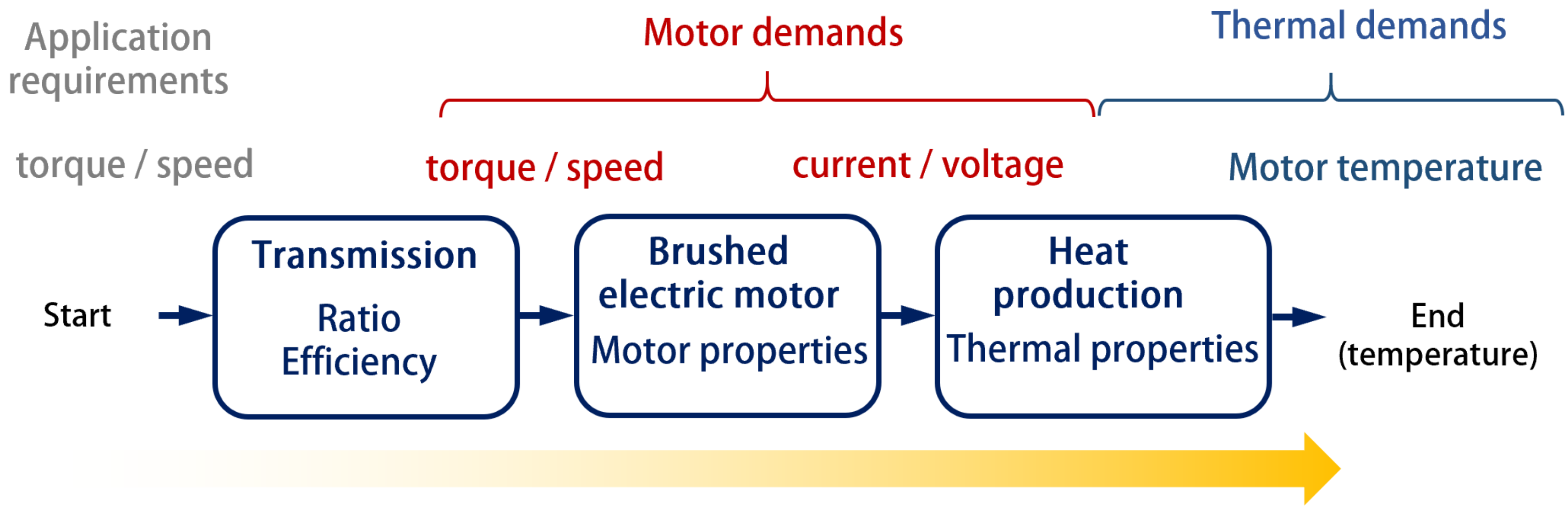
$$R_\sigma^{total} = R_\sigma^{wh} + R_\sigma^{ha}$$

$$\Delta\sigma = q(t) R_\sigma^{total} = q(t)\left(R_\sigma^{wh} + R_\sigma^{ha}\right)$$

$$q(t) = \frac{\sigma_w(t) - \sigma_h(t)}{R_\sigma^{wh}} = \frac{\sigma_h(t) - \sigma_a(t)}{R_\sigma^{ha}}$$

Ohm's law

Thermal Modeling



- Review of parameters needed for design framework
  - **Transmission** – efficiency (η)
  - **Motor** – resistance (R), inductance (L), torque constant (k_t), inertia (J), damping (b)
  - **Thermal** – thermal properties (R_σ^{total} or, R_σ^{wh} and R_σ^{ha}) or continuous current / torque for steady state analysis
  - **You choose** – application requirements, motor, transmission ratio (N), maximum voltage

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

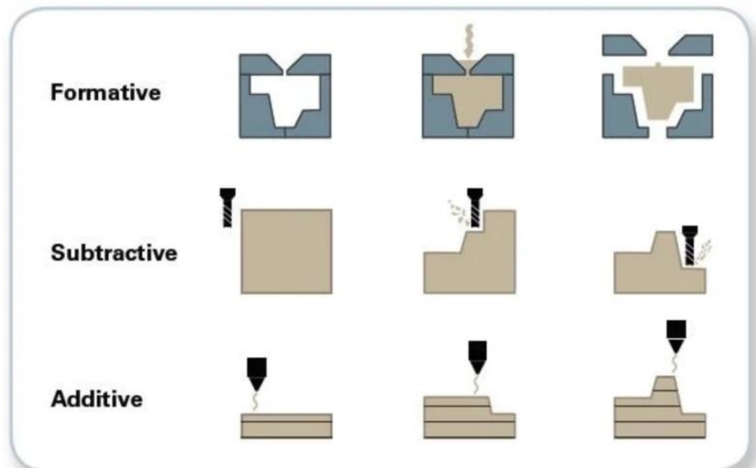
Heat production
Thermal properties

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**

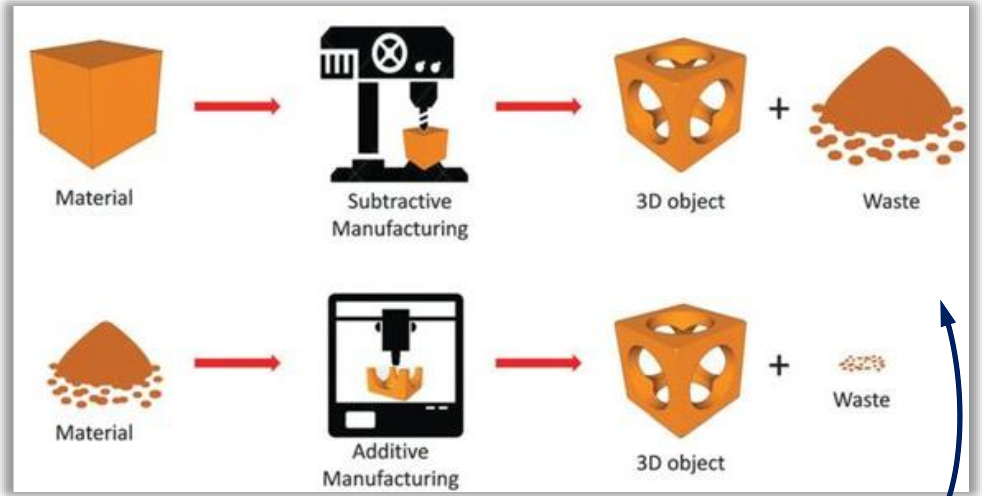
Some

What we will focus on in this course



Manufacturing Types

- Choice for subtractive vs. additive comes from feature sizing and available material properties, among other factors (more next slide)
- For rapid prototyping—the focus of this class—features should be on the scale ~0.1 mms to 100s of mms
  - Generally low loads (10s of Mpa or N/m^2)
  - Common materials: plastics, woods, ceramics, some metals
  - Fast iteration
- Subtractive
  - Milling
  - Turning / lathing
  - Laser / water cutting
- Additive
  - 3D printing
  - Types / techniques depend heavily on scale



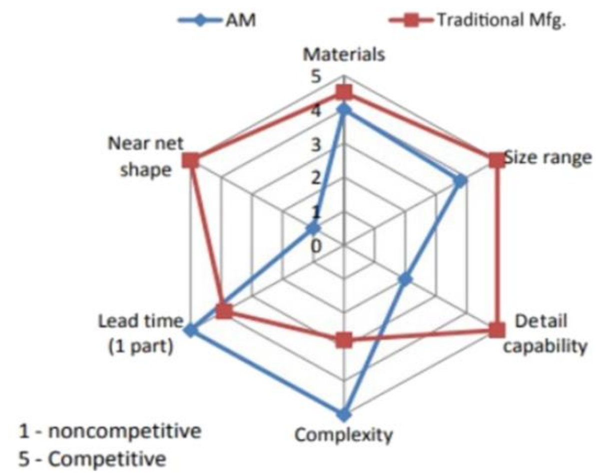
People study ways to improve the waste of traditional mfg.

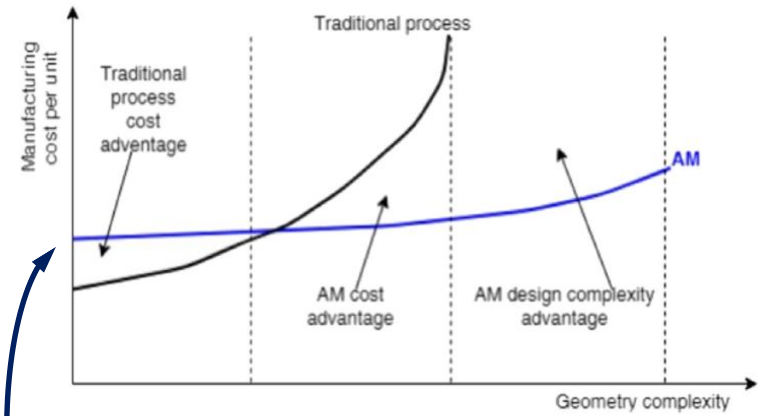
Chen et al. 2020

Manufacturing Types

AM = additive mfg. = 3D printing

- Advantages and disadvantages of 3D printing
- Active area of research
- In 2020, there was over 10k publications each year w/ 'additive mfg'
- 300% increase from 2015
- What accelerated 3D printer development
  - Improved components
  - Open-source, patent expirations, etc.
  - Better CAD software (like Solidworks)
- In this class, we'll learn a few different techniques used to make quick, nice looking, and capable robots





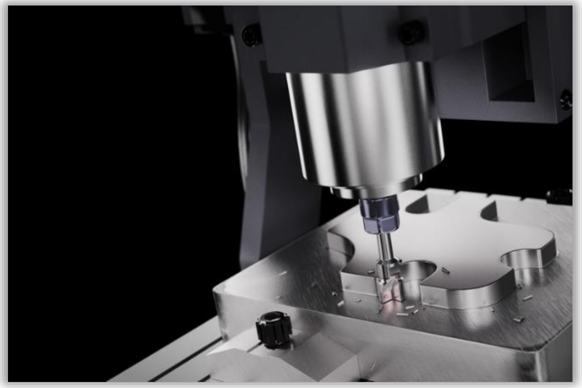
AM cost has become lower still

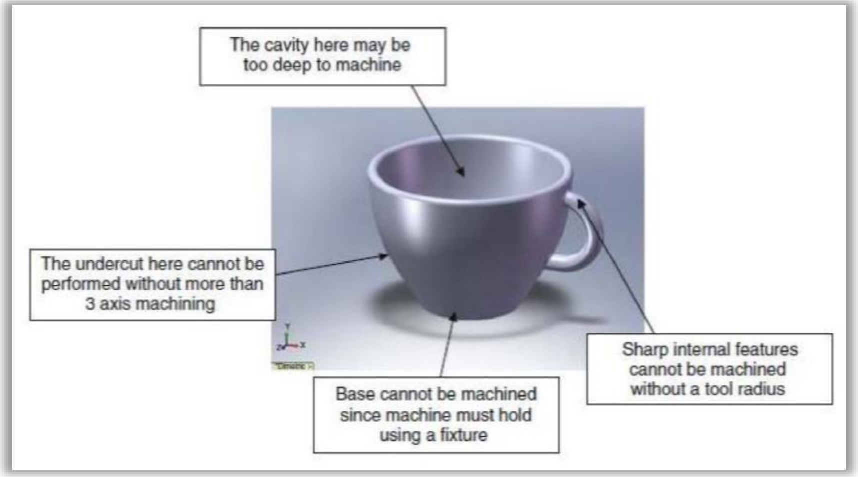
Krishna et al. 2021

Krishna et al. Dev. in additive manufacturing, Ch. 3, 2021 uploaded to Canvas\Resources

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

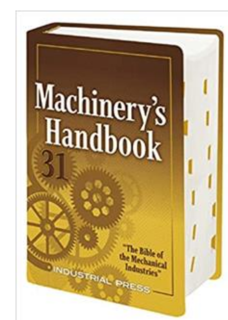
- Lathing – cutting or shaping with a *lathe*
  - Completed rotating a part and cutting at a radius
  - Other uses – woodworking / prototyping
- Design decisions can be made to take advantage of rapid prototyping tools
  - We are using laser-cut acrylic for this reason
- Another design consideration 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

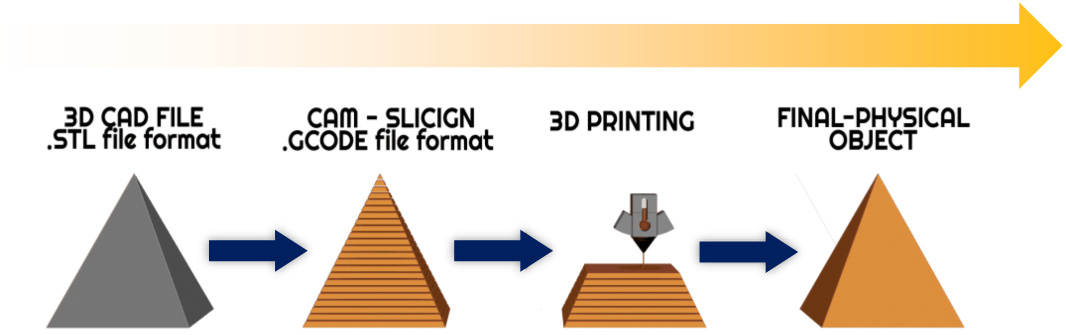
Tolerances also provided in large tables in this book



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

Additive Manufacturing / 3D Printing

Digital file created in Solidworks

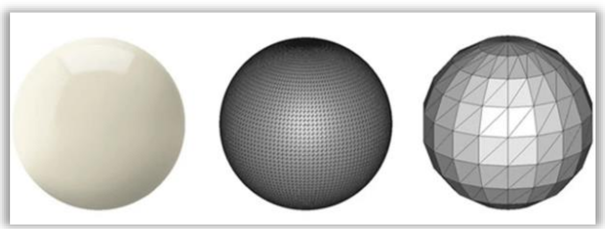


Prototype part ready for use

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

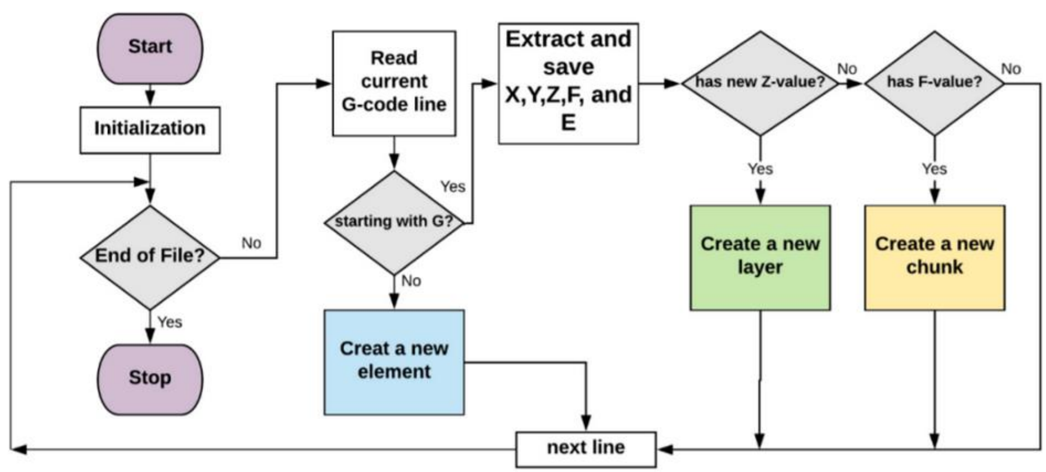
- A .gcode file is series of commands that tells the 3D printer what actions to perform—where to move, how fast, what temperature to set, etc.
- Each 3D printer expects the .gcode file to be formatted in a specific way based on the printers firmware.
- Two of the most common printer firmwares are RepRap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

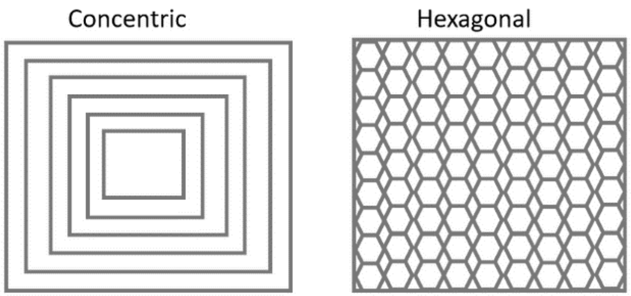
Example G-code snippet



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

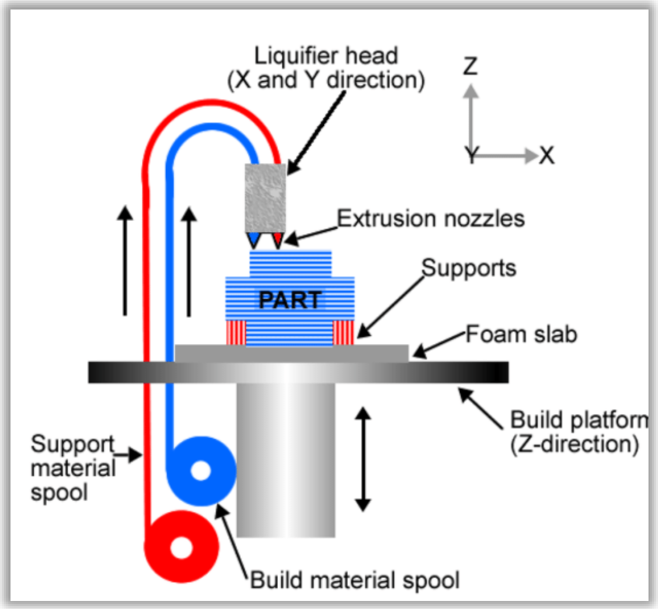
FDM

SLA

Polyjet

Fused Deposition Modeling (FDM)

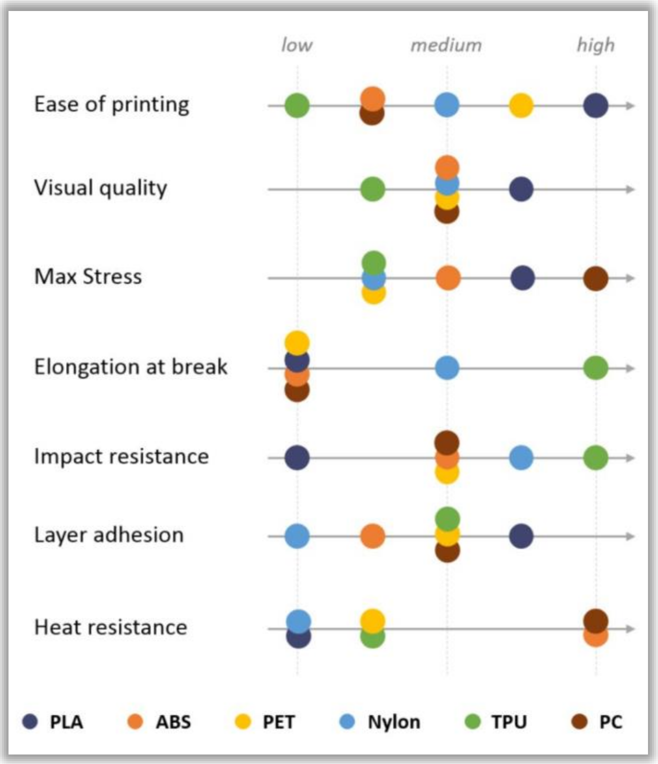
- One of the most common types 3D printers
- Heated plastic filament is extruded through a nozzle
- Common plastics: ABS, PLA, nylon
- Uses support material alongside build material to support parts they print
- Costs \$100s to \$10,000s



- 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

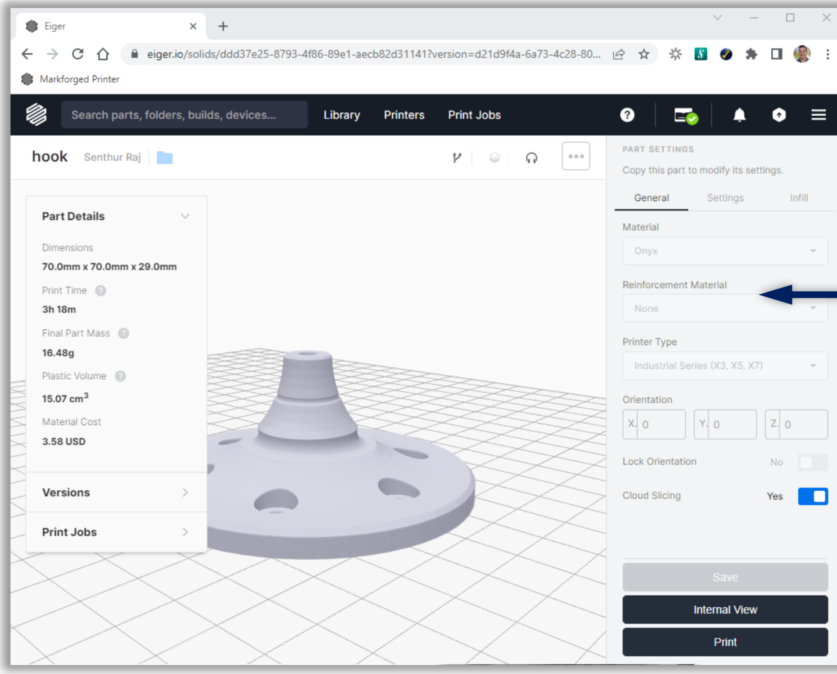
$800 Prusa (ABS)

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

Fused Deposition Modeling (FDM)

- Markforged / reinforced printing completed through a browser
- Continuous fiber!
- No slicing software needed
- Why? Markforged uses their own to add filament
- Carbon, fiberglass, Kevlar,
- We have one in FRB but not part of the makerspace

Browser-based printer interaction



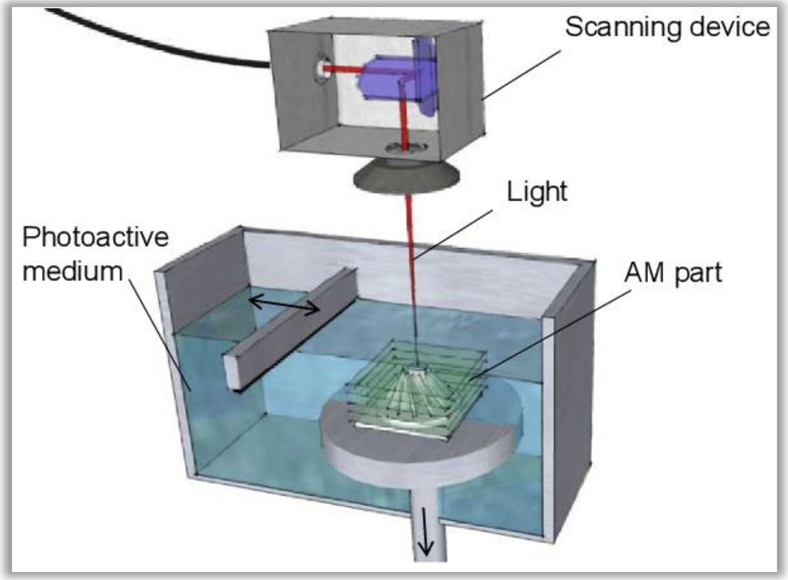
Add reinforcement here

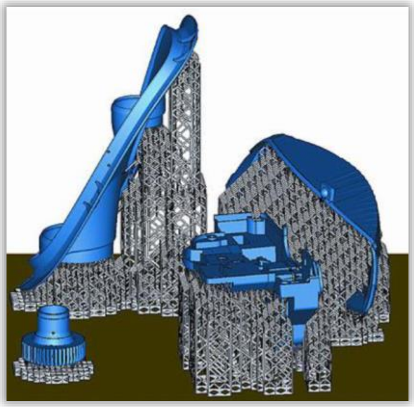
Example parts with different types of reinforcement

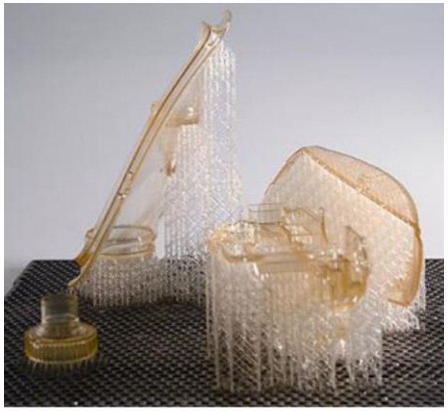
Stereolithography (SLA)

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
- No additional support material needed
- 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

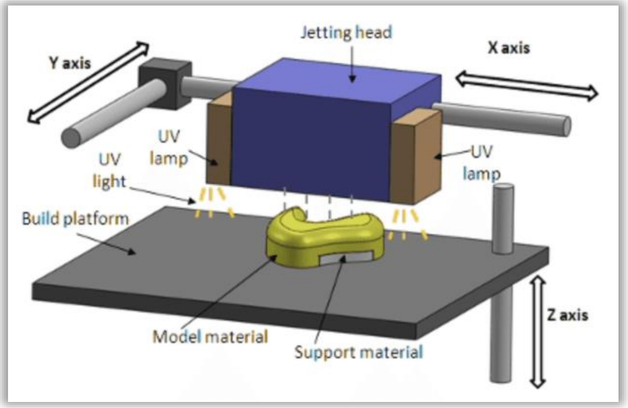






Polyjet Printers

- 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)

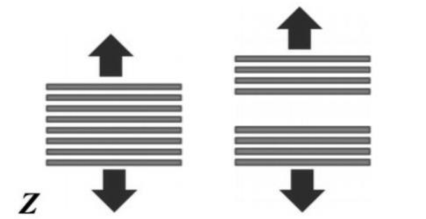


Stratasys Connex 500

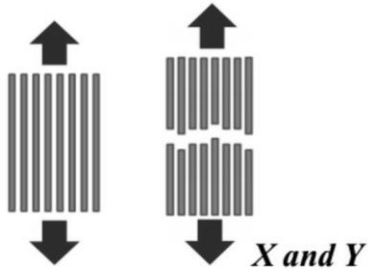
Best Practices – Additive Manufacturing

- 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%

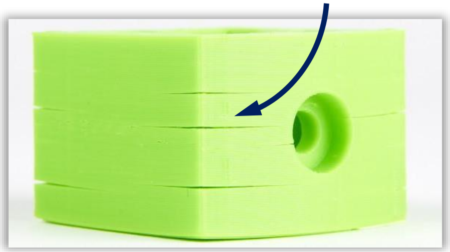
Weaker in Z direction (vertical)



Stronger in X-Y direction in build plane

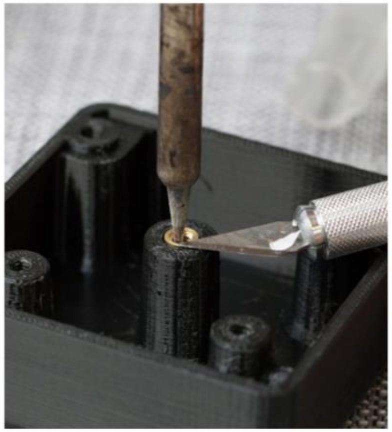


Layer separation

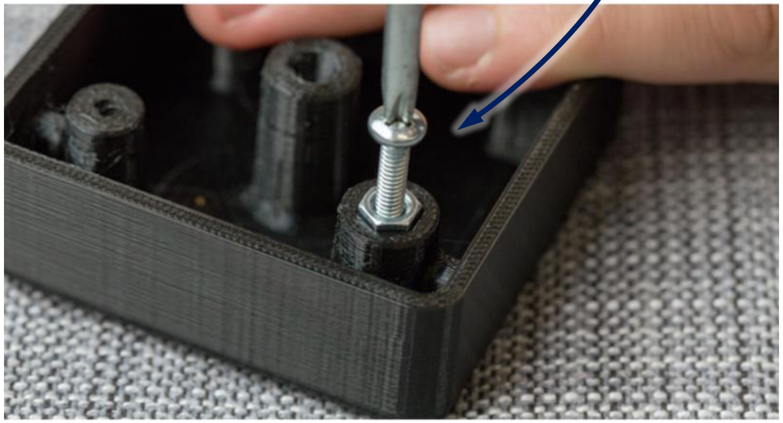


Best Practices – Additive Manufacturing

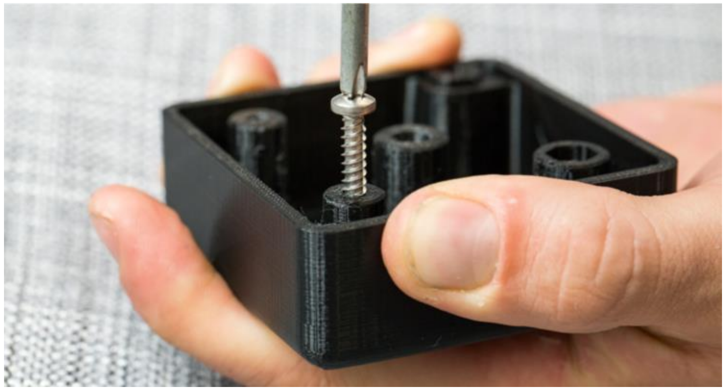
We use mostly these
in the ball-bot

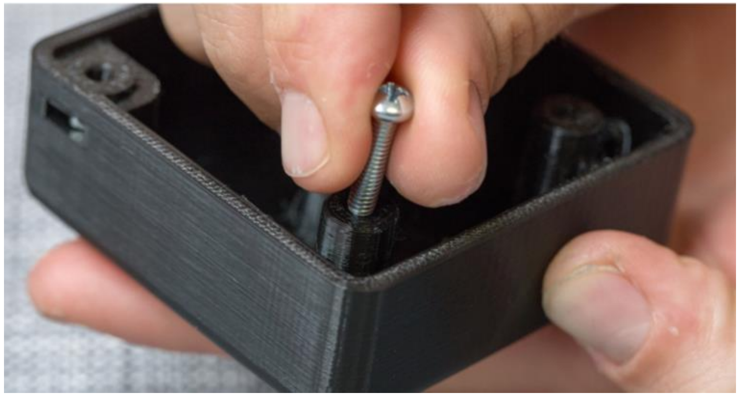
Threaded inserts can be heated and installed in a part. They come in both metric and English sizes. A soldering iron can be used to heat the insert.



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. Notice how much shallower the threads are compared to the self-tapping screw