Robotics 311 : How to build robots and make them move

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ROB 311 – Lecture 6

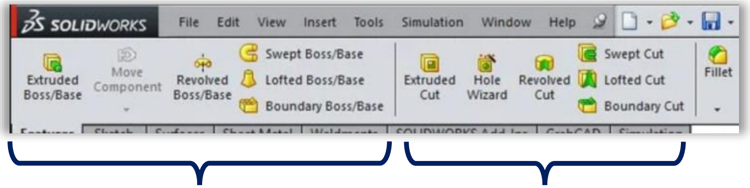
- Today:
  - Quick review of Solidworks operations
  - Creating assemblies
  - Thermal modeling
  - Quiz

- Announcements
  - Be sure to look at the MATLAB code that runs our analysis framework on the ball bot mechanics
  - The planar modeling will come up more when we discuss control
  - HW2 Q5 hints:
    - Springs and damper are 'rotational' meaning you do not need to know the distance along the rod
    - It's not just inertia that is reflected that is reduced by N^2 through a transmission... It also pertains to stiffness and damping

Lab 3 – Solidworks - 3D Operations

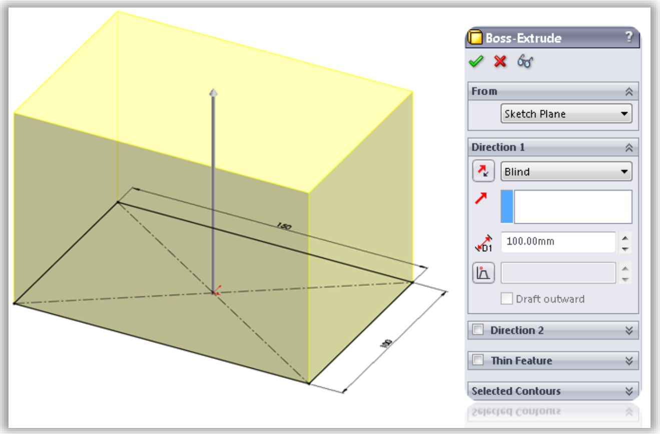
- Solid modeling is a tool used to create representations of 3D parts
- Think of it as virtual clay (with geometry!)
- The parts can be exported for instructions of 3D printers and laser cutters
- Parts are created using geometric operations
- Operations are stacked to create more complex shapes
- Parts can be assembled into Assemblies
- Parts can be created using simple operations (extrude, revolve, loft, etc.)
- Material can be removed with cutting operations (extrude cut, revolve cut, etc.)

More operations →



Create features

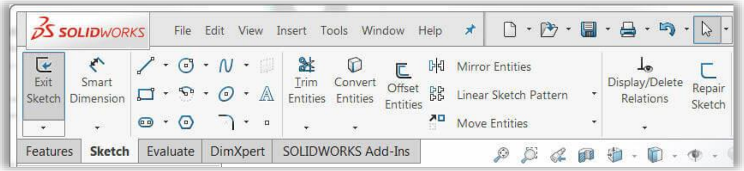
Cut features



Extruding a rectangle from a sketch

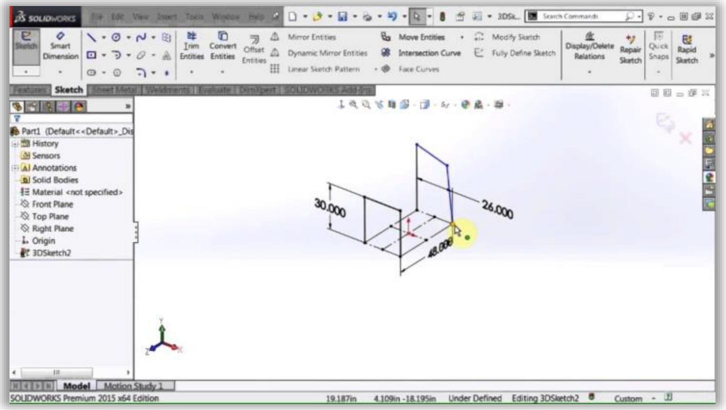
Lab 3 – Solidworks - Sketching

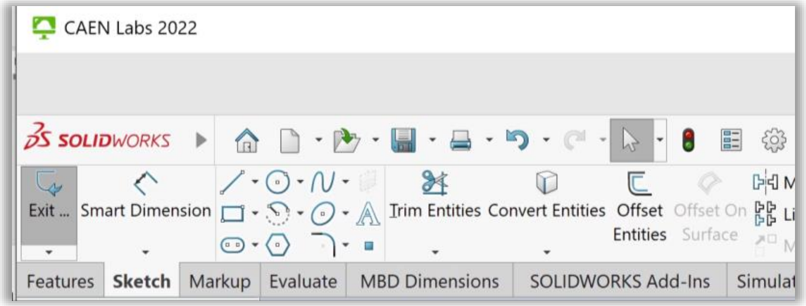
- Each operation begins with a sketch
- Sketches are made on a plane that is selected (shape face, plane, etc.)
- The sketch defines what is being extruded / cut
- Building sketches includes simple operations (lines, circles, fillets, etc.)
- Sketches can be ‘trimmed’
- ‘Smart Dimension’ is used to add dimensions
- Exiting the sketch will bring you back out to the original (3D) operation to select thickness



Create lines /shapes, etc.

Convert, patterns, etc.





Exit Sketch and Smart Dimension buttons

Lab 3 – Designing Ball-Bot Structures

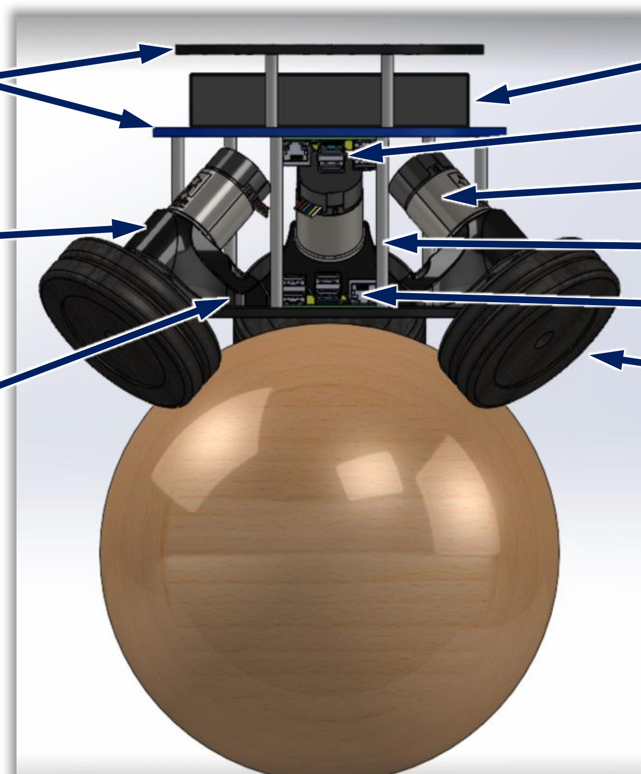
- Over the next few labs, we will build the structures of the ball-bot
- We will begin with the motor mounts then move to the acrylic structures
- You will use these part files to have your designs made

We're going to design and make these

Three different acrylic plate structures
Laser cut

Motor mounts (x3)
3D printed - FDM

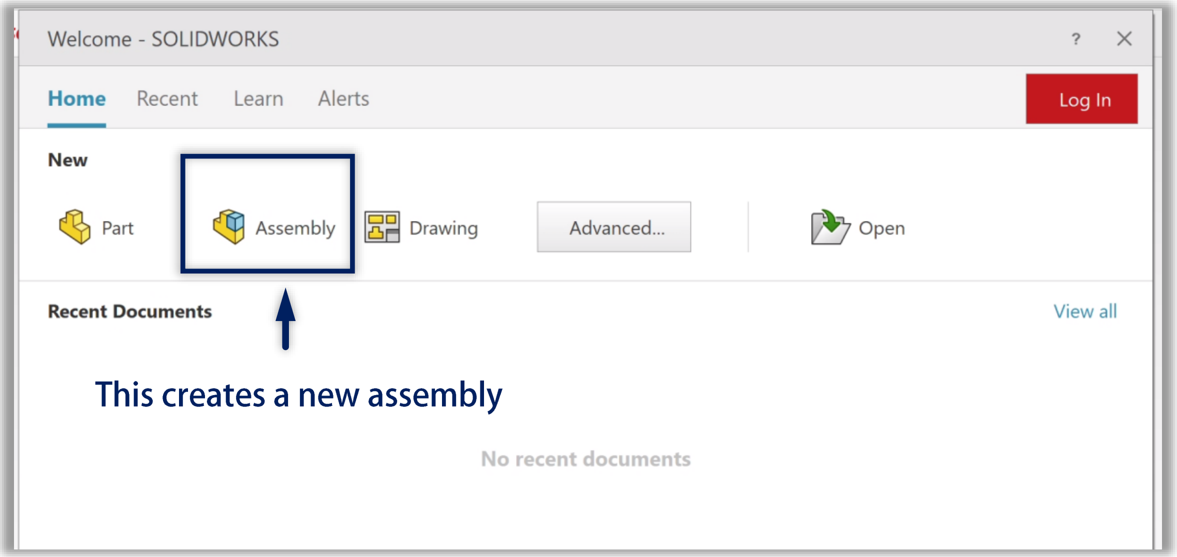
RPi isolator plate (acrylic)
Laser cut



Motor mounts – medium difficulty
Acrylic plates - easy

Lab 3 – Creating Assemblies

- A number of you were asking questions related to creating assemblies
- Parts can be joined together for visualization (and editing) in assemblies

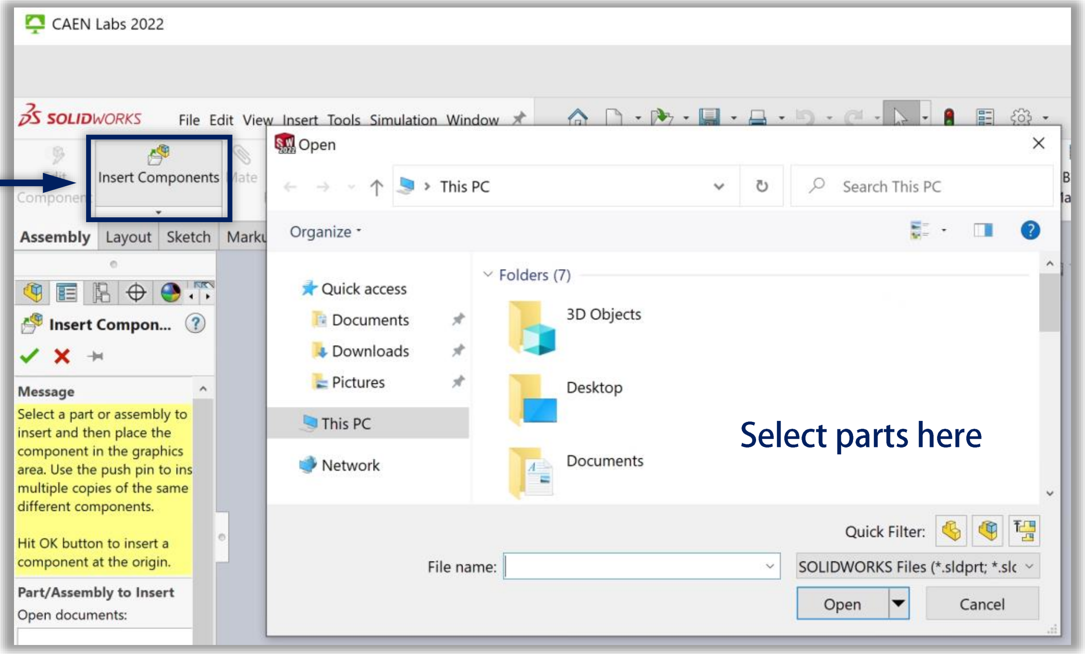


- Then you add part and relationships called 'mates' to define how the parts fit together

Lab 3 – Adding Parts to Assemblies

- Parts are added by

Parts are added to a new assembly using



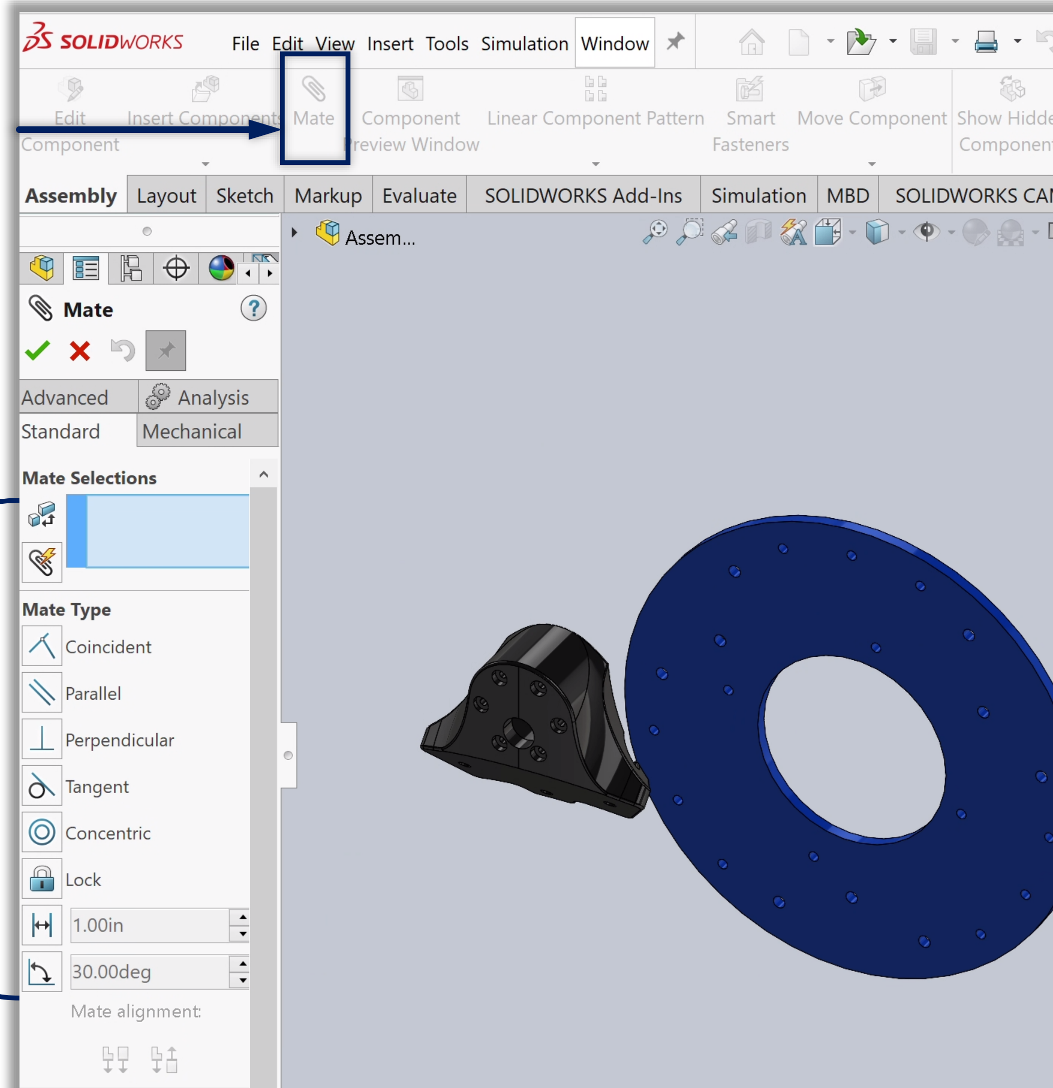
- Once added, place the parts in the assembly workspace using your mouse
- The parts are added to the assembly have 6 DOFs natively
    - They can rotate and translate in three axes and require mates to bind them together

Lab 3 – Adding Mates in Assemblies

- Mates are added by

Mates are added using

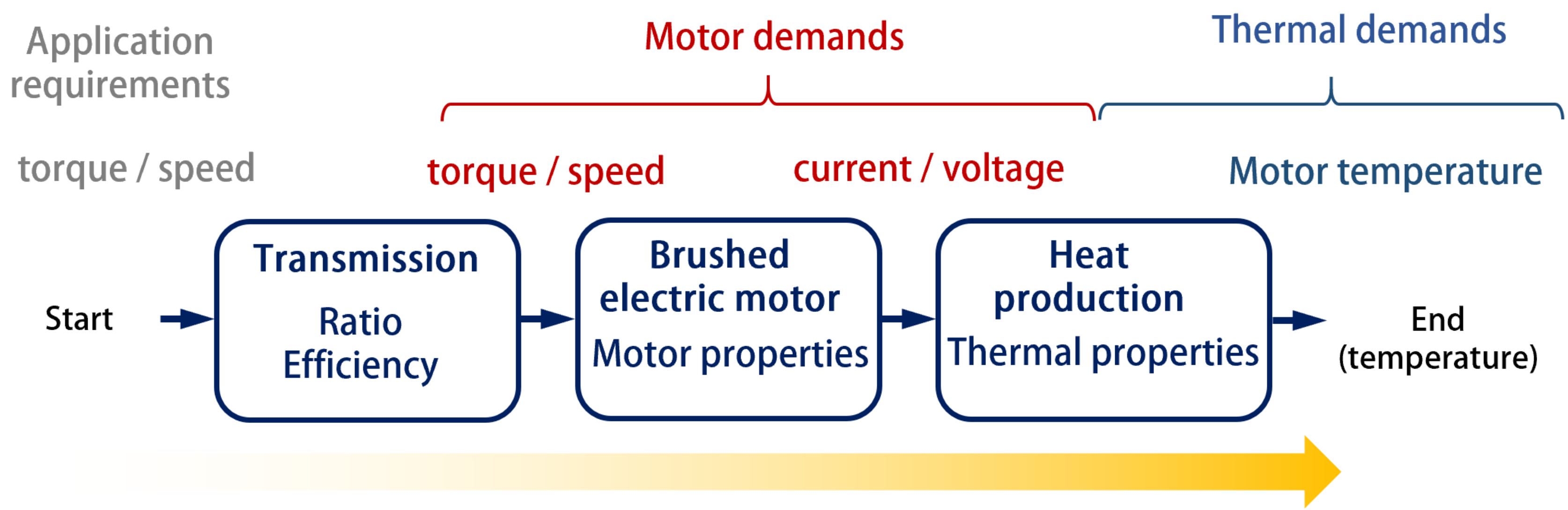
- Mate types described based on their physical function
- They different numbers of degrees
- ~Listed in increasing number of DOFs constrained
- Files of given parts (motor, standoffs, etc.) add to lab folder



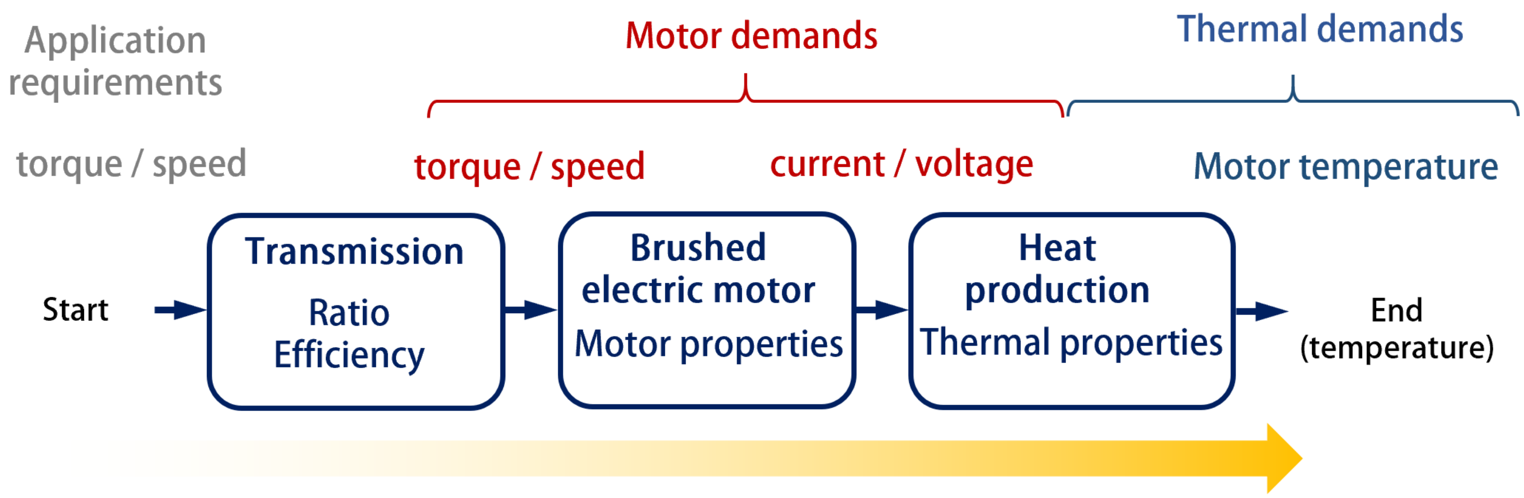
Mate types available

Design Analysis Framework

- So, where are we?
- Learned basics of
  - Understanding requirements and what we want our system to do
  - Use those requirements to determine important design parameters
  - Now we want to confirm our design is feasible by verifying the thermal response



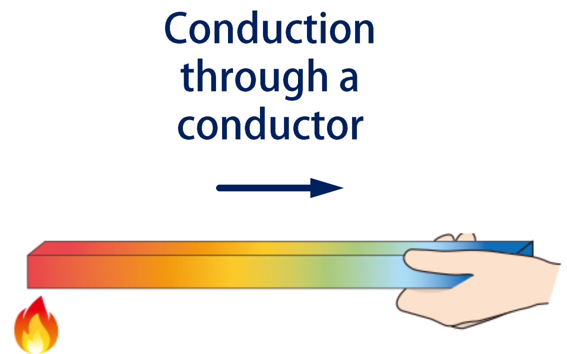
Design Analysis Framework



- 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

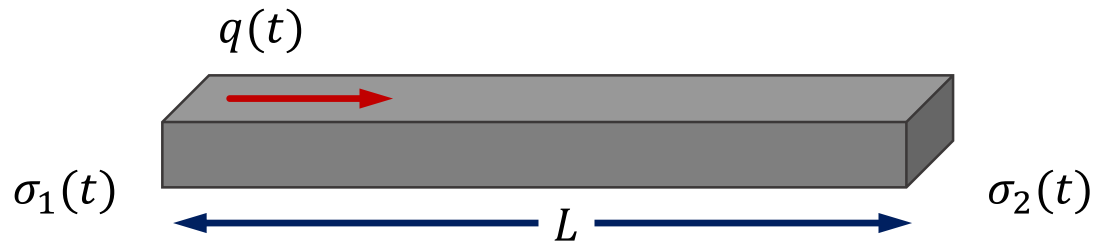
Thermal Modeling

- 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



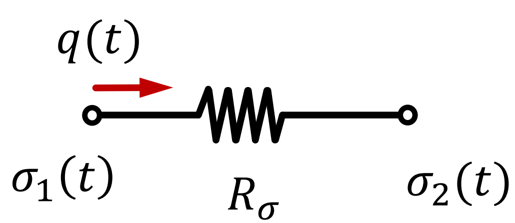
- Thermal resistivity, units K/W is below, using thermal conductivity κ (W/mK)

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

- Thus,

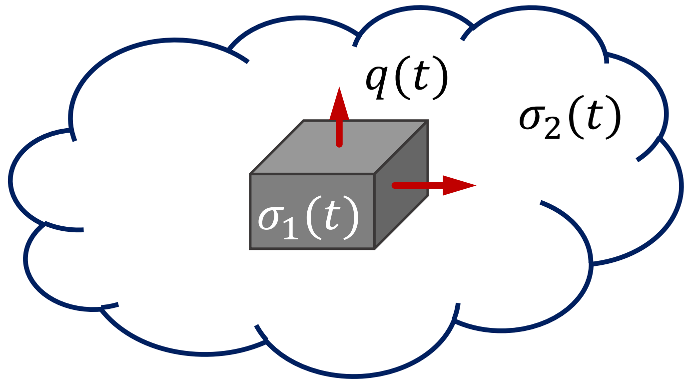
$$q(t) = \frac{\sigma_1(t) - \sigma_2(t)}{R_\sigma}$$

This looks familiar - Thermal version of Ohm's Law



Thermal Modeling

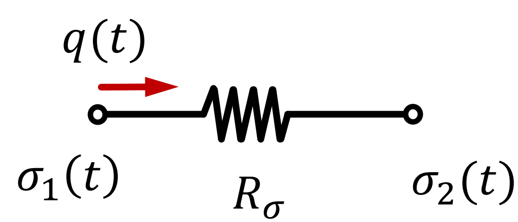
- Convection



- 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)

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

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



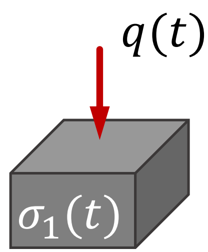
- R_σ can be changed with heat sinks, etc.

Thermal Modeling

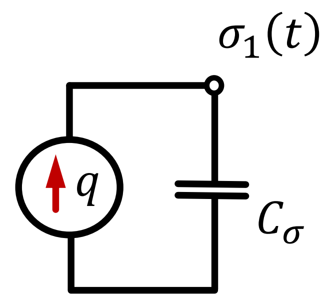
- Thermal capacitance (also called thermal mass)
- Describes an objects ability to store heat energy

$$C_\sigma = mc_p$$

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



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



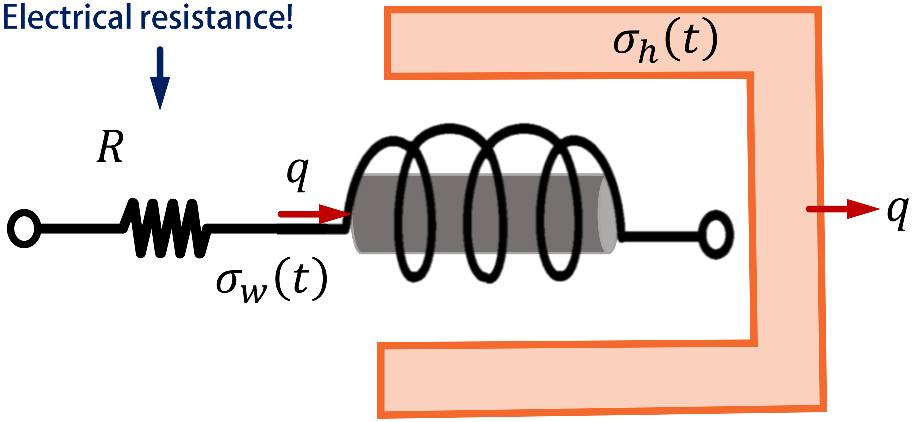
- Thermal systems have the same relationships as electrical systems
  - Voltage is analogous to temperature (effort)
  - Current is analogous to heat flux (flow)
  - Resistances and capacitances

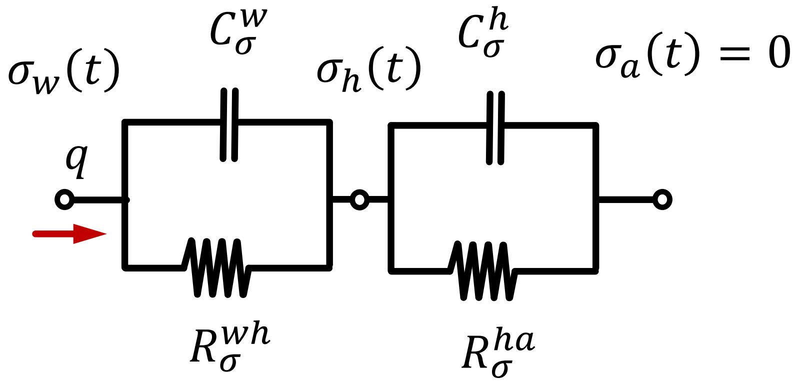
Thermal Modeling Example

This is a simplification (caps are both grounded)

- How do we use this to analyze motor thermal response?
- Develop thermal circuit:

Electrical resistance!





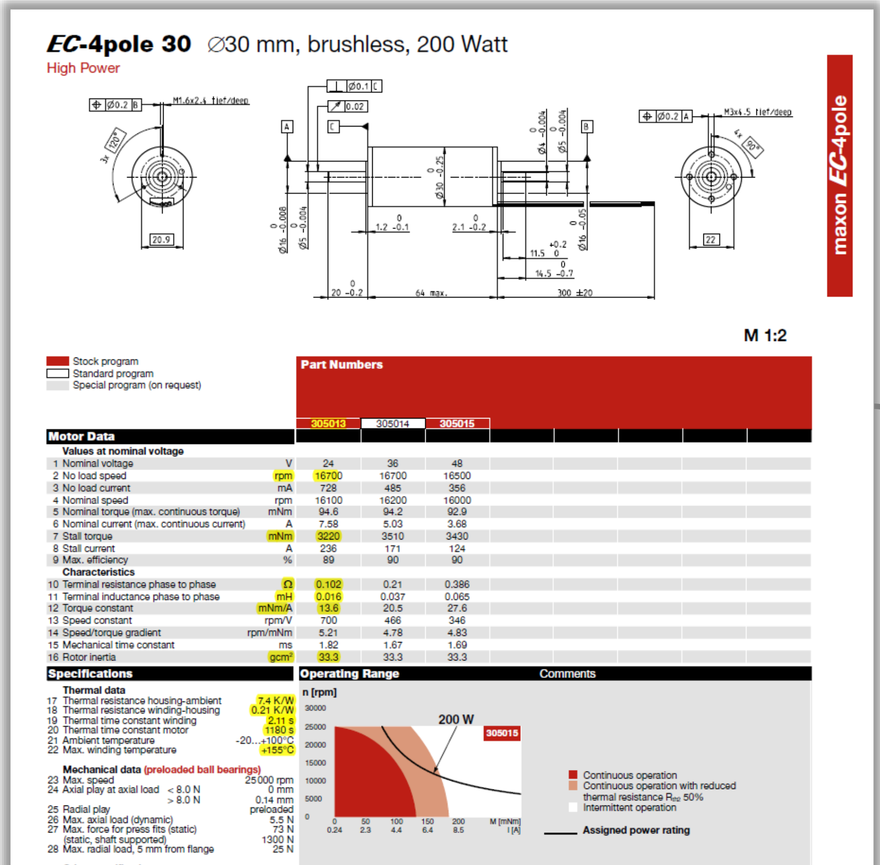
- What generates heat flux q? $q(t) = i_w^2(t)R$
- How to predict temperatures? Use KVL / KCL (or impedance analysis)

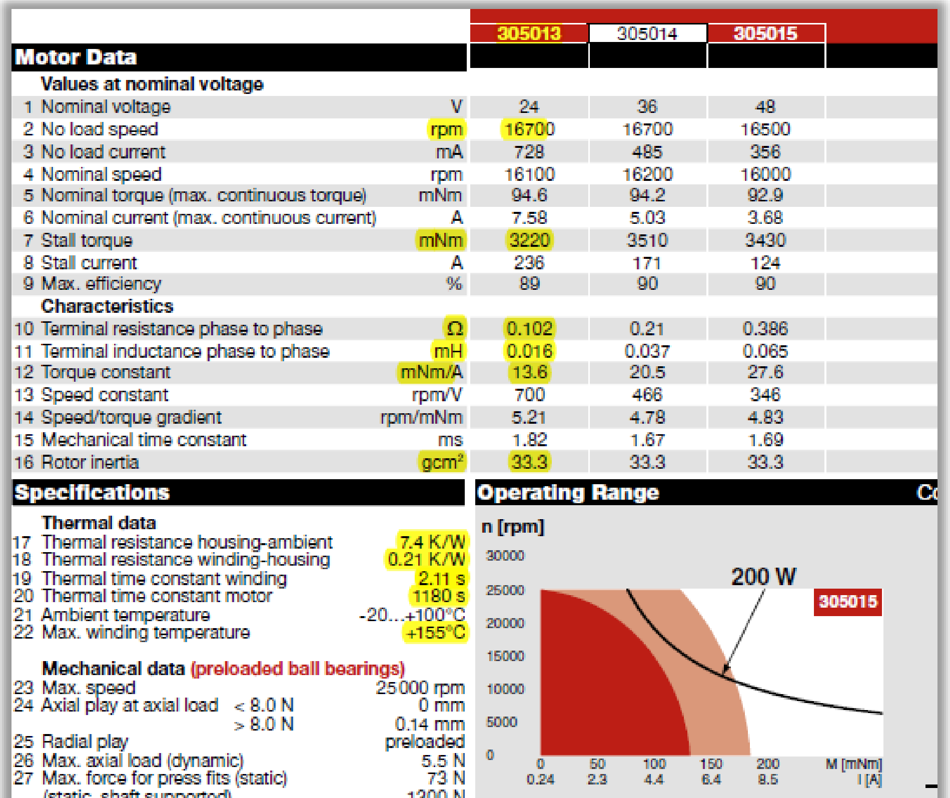
$$C_\sigma^{wh}\frac{d}{dt}(\sigma_w - \sigma_h) + \frac{1}{R_\sigma^{wh}}(\sigma_w - \sigma_h) = q = C_\sigma^{ha}\frac{d}{dt}\sigma_h + \frac{1}{R_\sigma^{ha}}\sigma_h$$

- Convenient for transfer function analysis

Thermal Modeling Example

- Thermal modeling parameters found in motor datasheets, online, measured





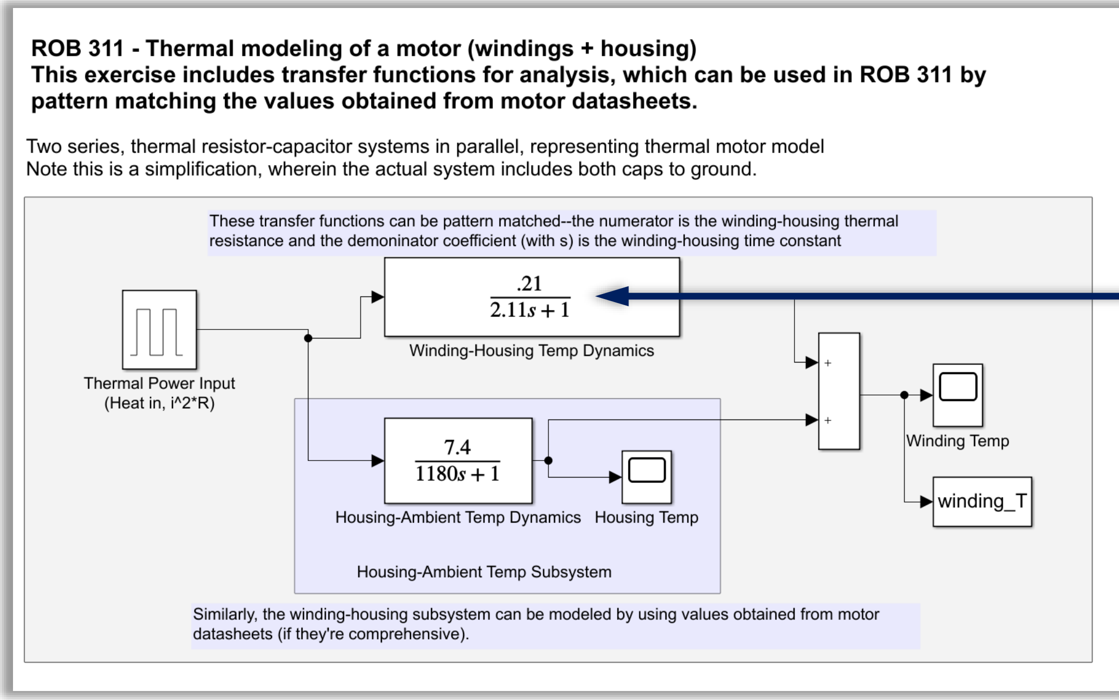
		305013	305014	305015
Motor Data				
Values at nominal voltage				
1 Nominal voltage	V	24	36	48
2 No load speed	rpm	16700	16700	16500
3 No load current	mA	728	485	356
4 Nominal speed	rpm	16100	16200	16000
5 Nominal torque (max. continuous torque)	mNm	94.6	94.2	92.9
6 Nominal current (max. continuous current)	A	7.58	5.03	3.68
7 Stall torque	mNm	3220	3510	3430
8 Stall current	A	236	171	124
9 Max. efficiency	%	89	90	90
Characteristics				
10 Terminal resistance phase to phase	Ω	0.102	0.21	0.386
11 Terminal inductance phase to phase	mH	0.016	0.037	0.065
12 Torque constant	mNm/A	13.6	20.5	27.6
13 Speed constant	rpm/V	700	466	346
14 Speed/torque gradient	rpm/mNm	5.21	4.78	4.83
15 Mechanical time constant	ms	1.82	1.67	1.69
16 Rotor inertia	gcm²	33.3	33.3	33.3

Specifications

Thermal data	
17 Thermal resistance housing-ambient	7.4 K/W
18 Thermal resistance winding-housing	0.21 K/W
19 Thermal time constant winding	2.11 s
20 Thermal time constant motor	1180 s
21 Ambient temperature	-20...+100°C
22 Max. winding temperature	+155°C
Mechanical data (preloaded ball bearings)	
23 Max. speed	25000 rpm
24 Axial play at axial load < 8.0 N	0 mm
> 8.0 N	0.14 mm
25 Radial play	preloaded
26 Max. axial load (dynamic)	5.5 N
27 Max. force for press fits (static)	73 N
(static, shaft supported)	1300 N

Thermal Modeling Example

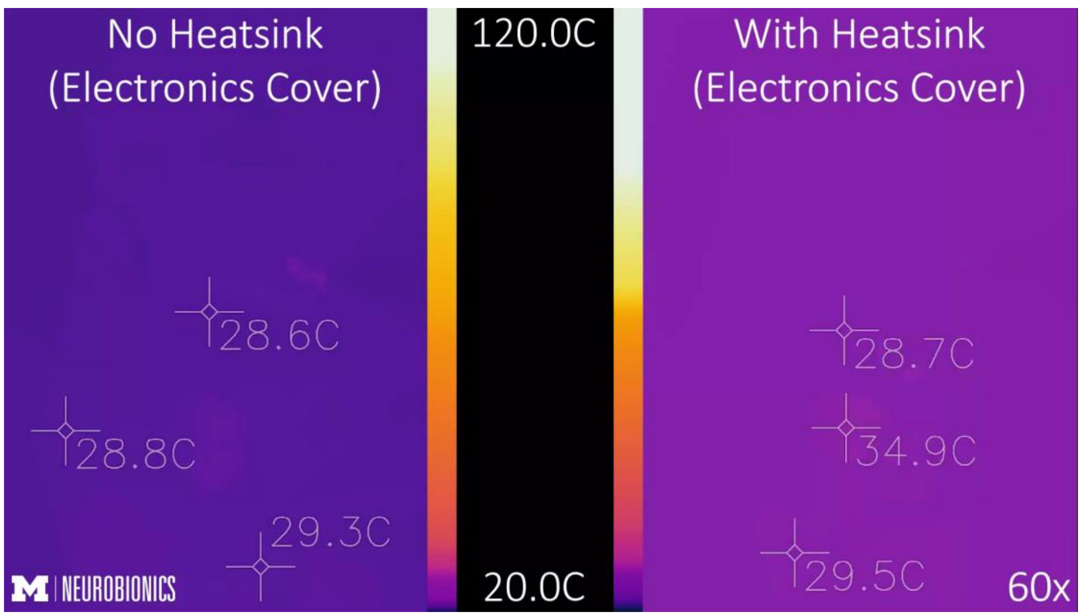
- These analyses can be completed using Simulink
- I will show a transfer function based modeling solution – feel free to use
- Steady state temperatures can be found using Ohm's Law
- First, lets look at a Simulink example

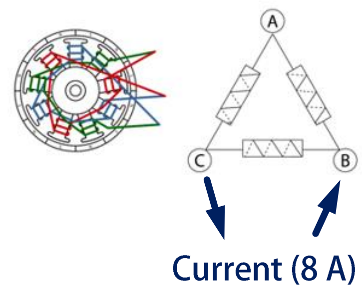


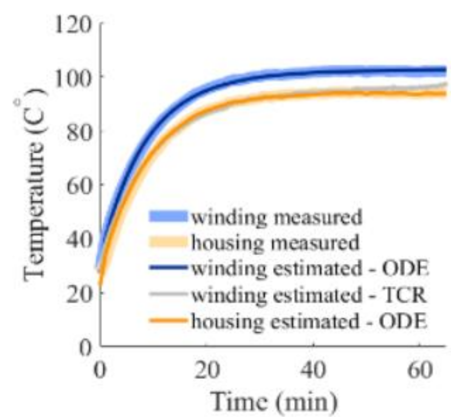
These are of the form:
$\frac{R_\sigma}{R_\sigma C_\sigma s+1}$ or
$\frac{R_\sigma}{\tau_\sigma s+1}$ where
τ_σ is the thermal time constant

Thermal Modeling – Research Example

- What if these values are unknown?
  - Common with newer motors used for drone industry





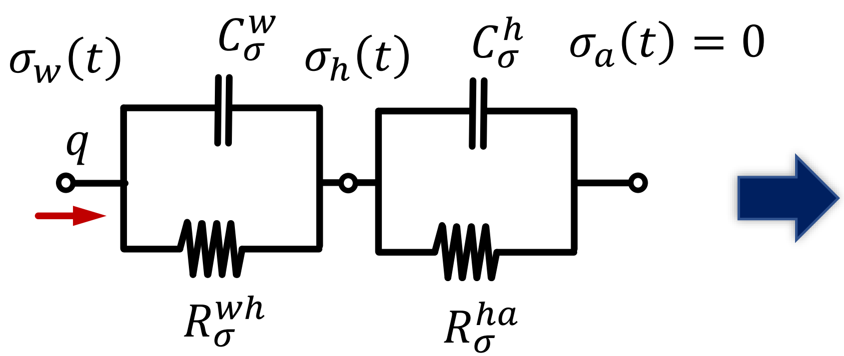


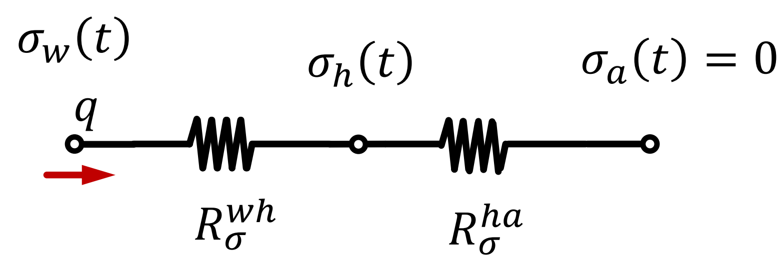
Thermal Modeling

- 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 (slide 20)
- In steady state, the system behaves like two resistors in series





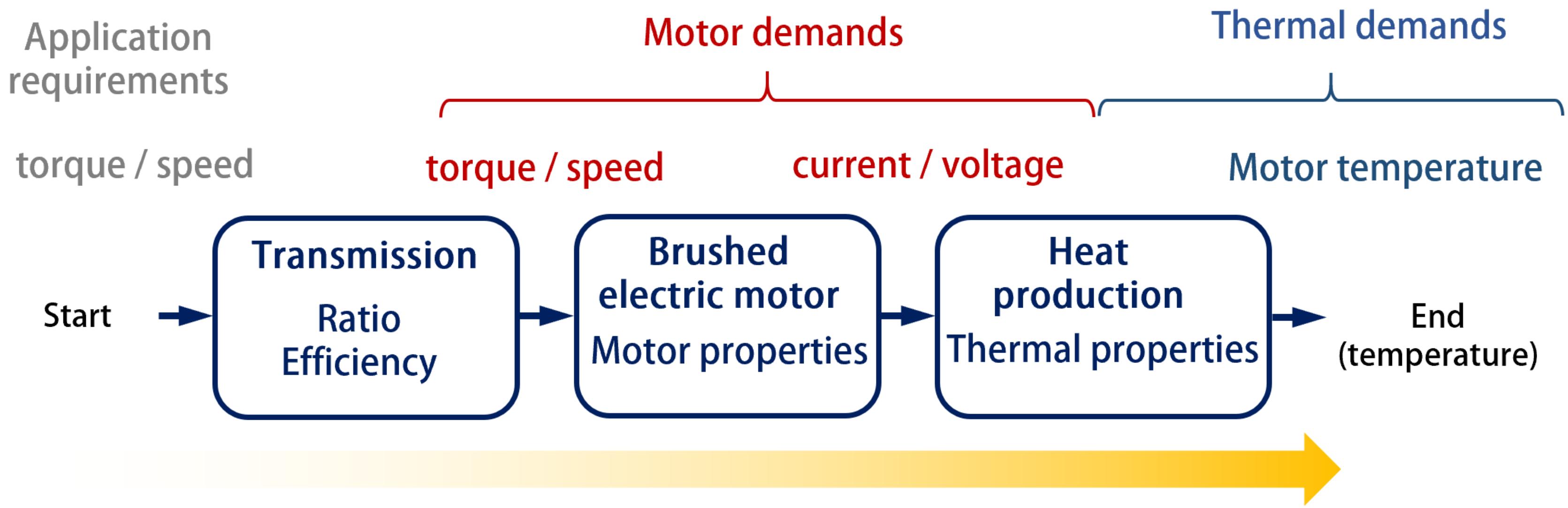
$$R_\sigma^{total} = R_\sigma^{wh} + R_\sigma^{ha}$$

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

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

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