2.72 Elements of Mechanical Design
Spring 2009

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Elements of Mechanical Design

Lecture 02: Review

Intent

High-level review of undergrad material as applied to engineering decision making

NOT an ME "redo" or a "how to" recitation

Import

Main goal of 2.72 is to teach you how to integrate past knowledge to engineer a system

Given this, how do I engineer a mechanical system?
modular→simple→complex→system

2.001, 2.002

2.003, 2.004

2.005, 2.006

2.007, 2.008

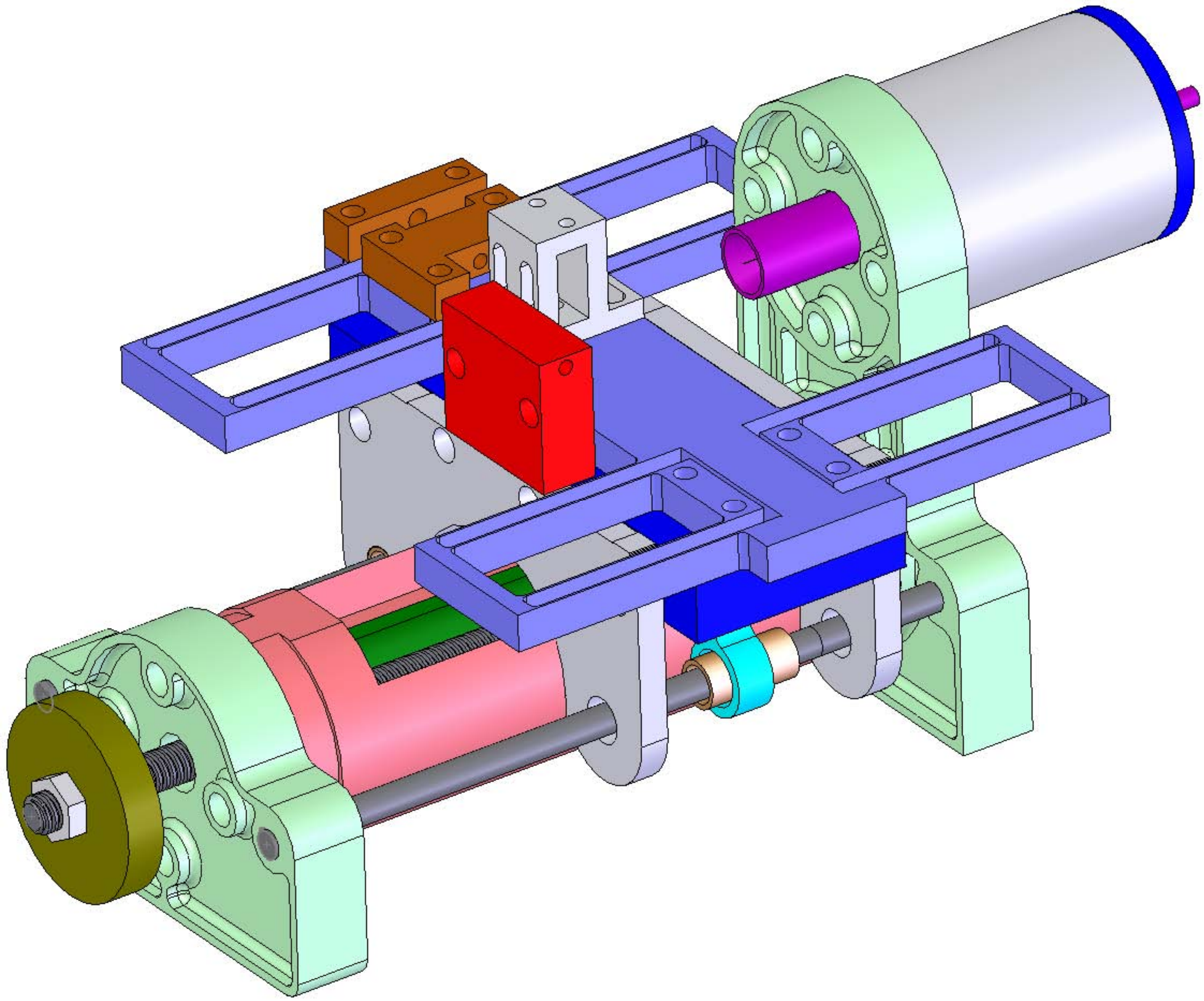
Use of core ME principles that you know…

2.001, 2.002

2.003, 2.004

2.005, 2.006

2.007, 2.008



Impact

Understand why & how we will use parts of ME core knowledge

Problem set → Engineering

Future help

We can’t use lecture time to redo the early curriculum

BUT

We are HAPPY to help outside of lecture IF you’ve tried

Schedule and reading assignment

Reading quiz

Changing from sponge to active mode

Lecture	**Hands-on**
Mechanics	Mechanics
Dynamics	Dynamics
Heat transfer	Heat transfer
Matrix math	Matrix math

Reading assignment

- Shigley/Mischke
  - *Sections 4.1–4.5: 08ish pages & Sections 5.1–5.5: 11ish pages*
  - *Pay special attention to examples 4.1, 4.4, 5.3 , and 5.4*

Mechanics

Free body diagrams

Useful for:

- Equilibrium
- Stress, deflection, vibration, etc…

$$\Sigma \vec{F} = 0 = m\vec{a}$$

$$\Sigma M = 0 = I\vec{\alpha}$$

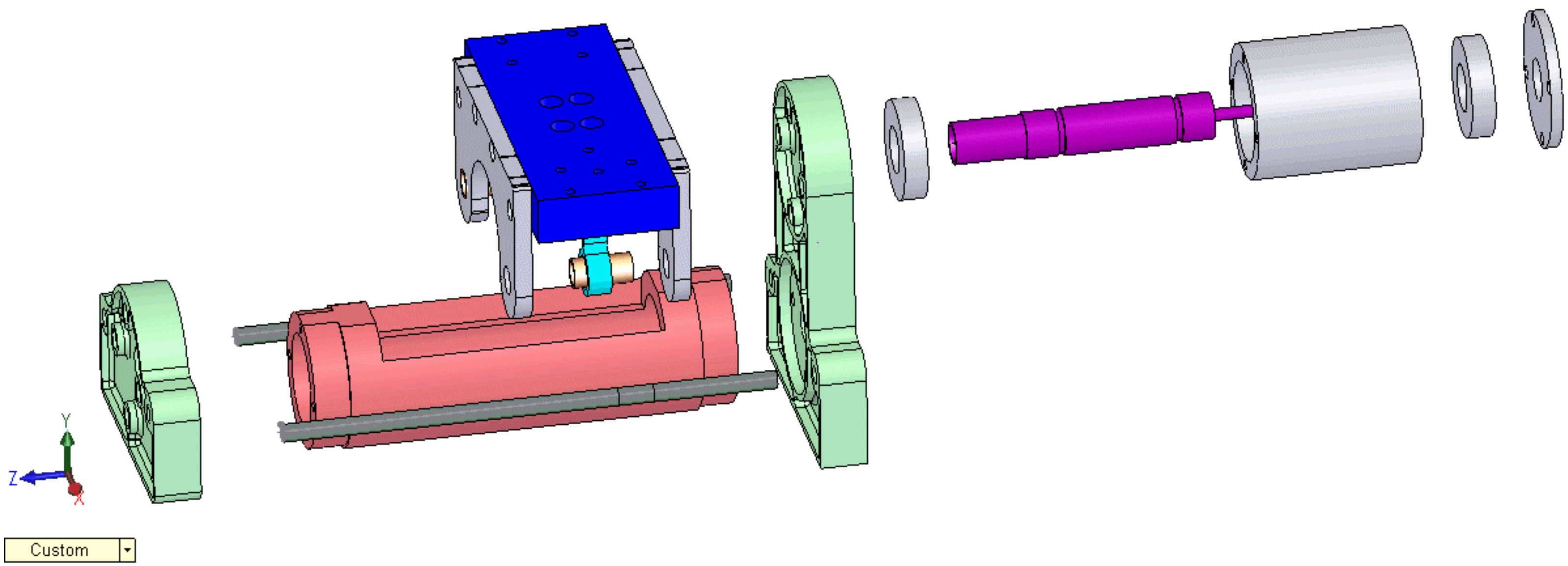
Why do we ALWAYS use free body diagrams?

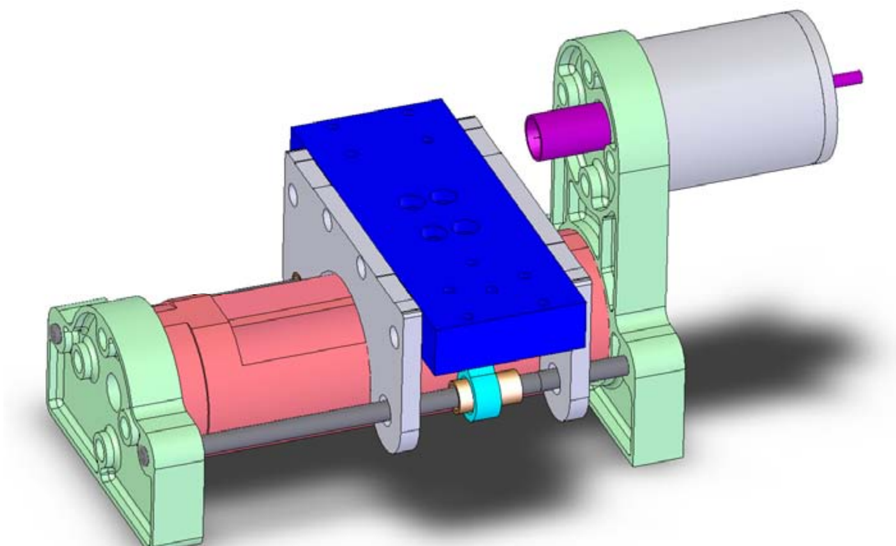
- Communication
- Thought process
- Documentation

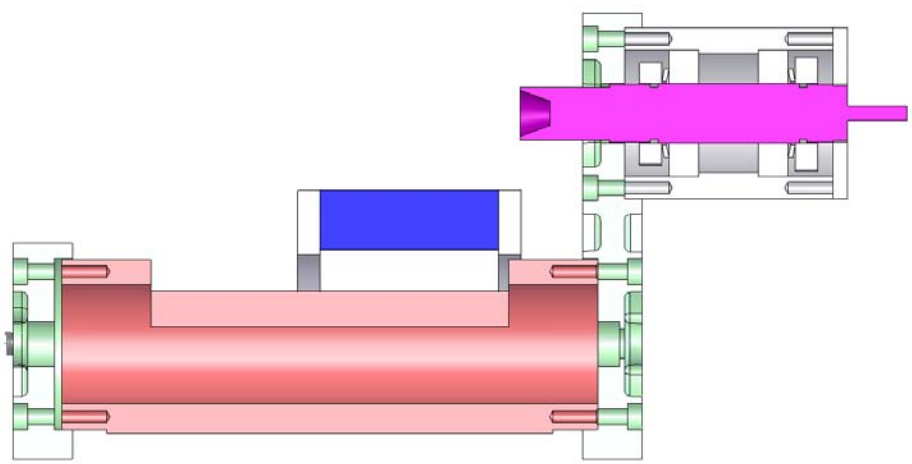
How will we use free body diagrams?

- We are dealing with complex systems
- We will break problem into modules
- We will model, simulate and analyze mechanical behavior
- Integrate individual contributions to ascertain system behavior

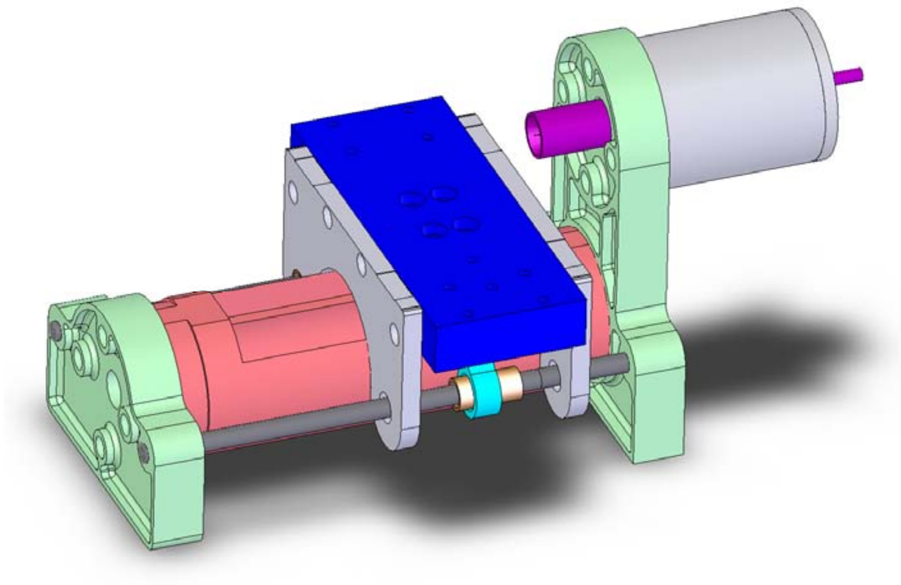
Free body diagrams: Bearings/rails

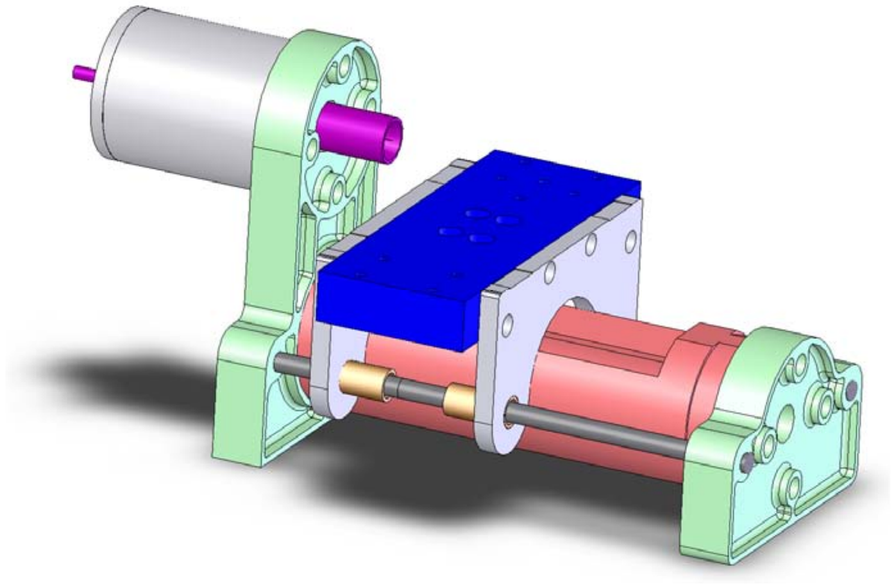


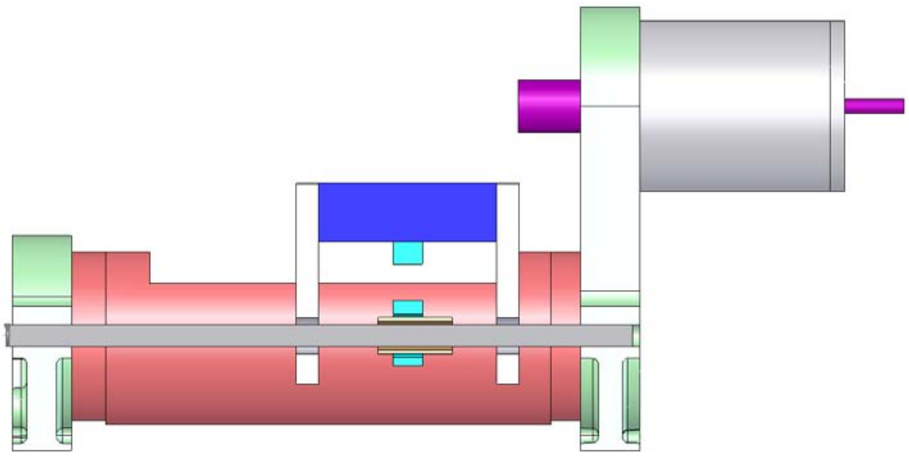


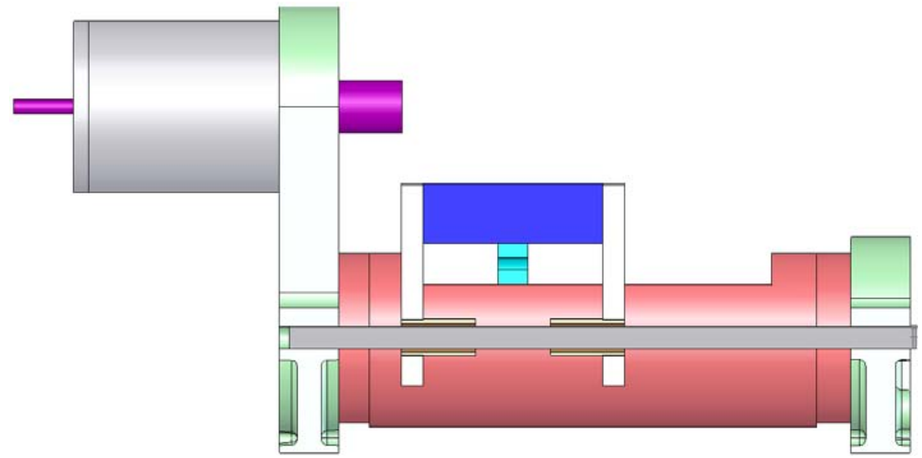


Free body diagrams: Bearings/rails

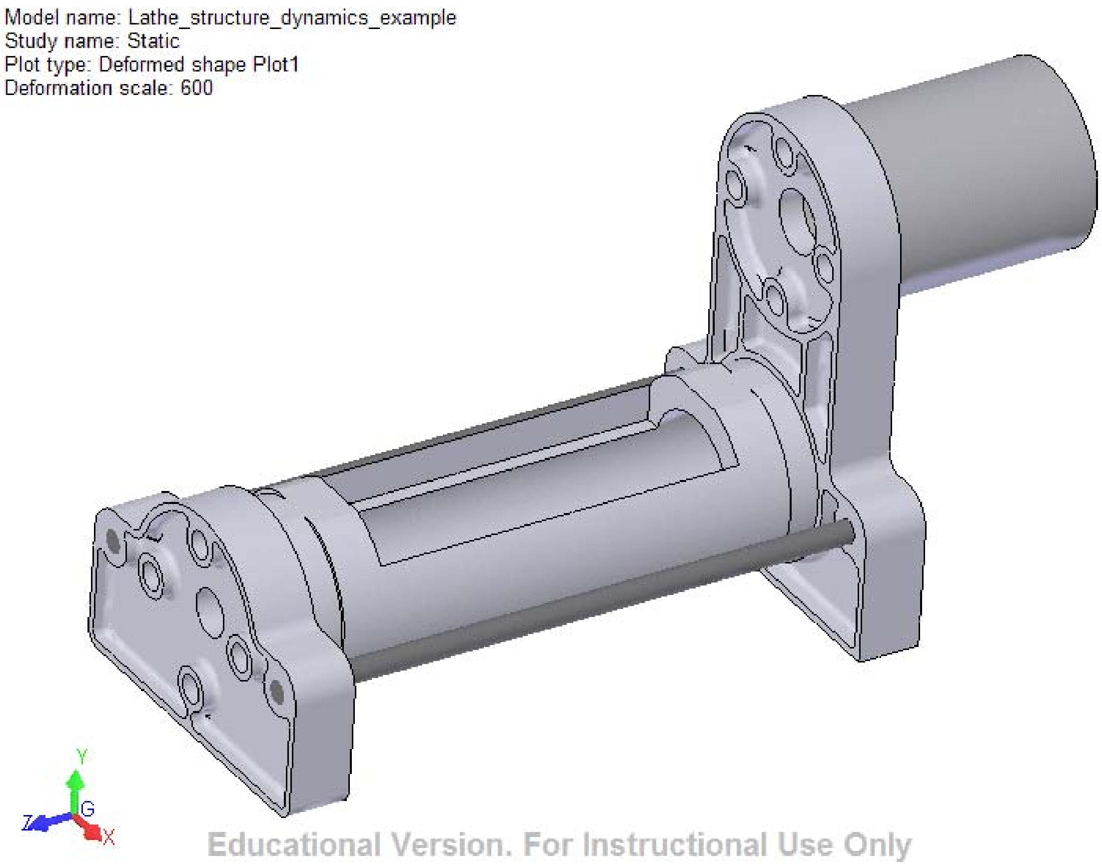


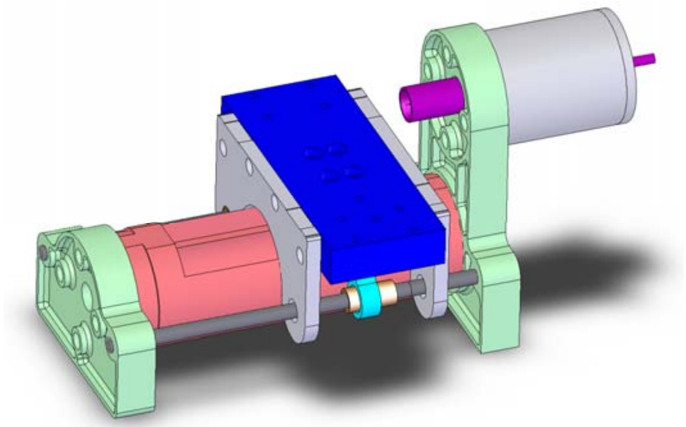


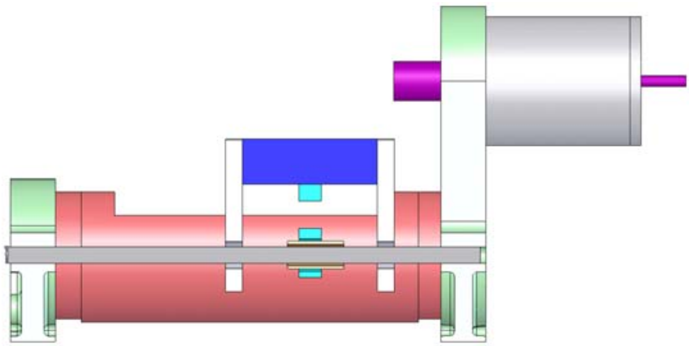




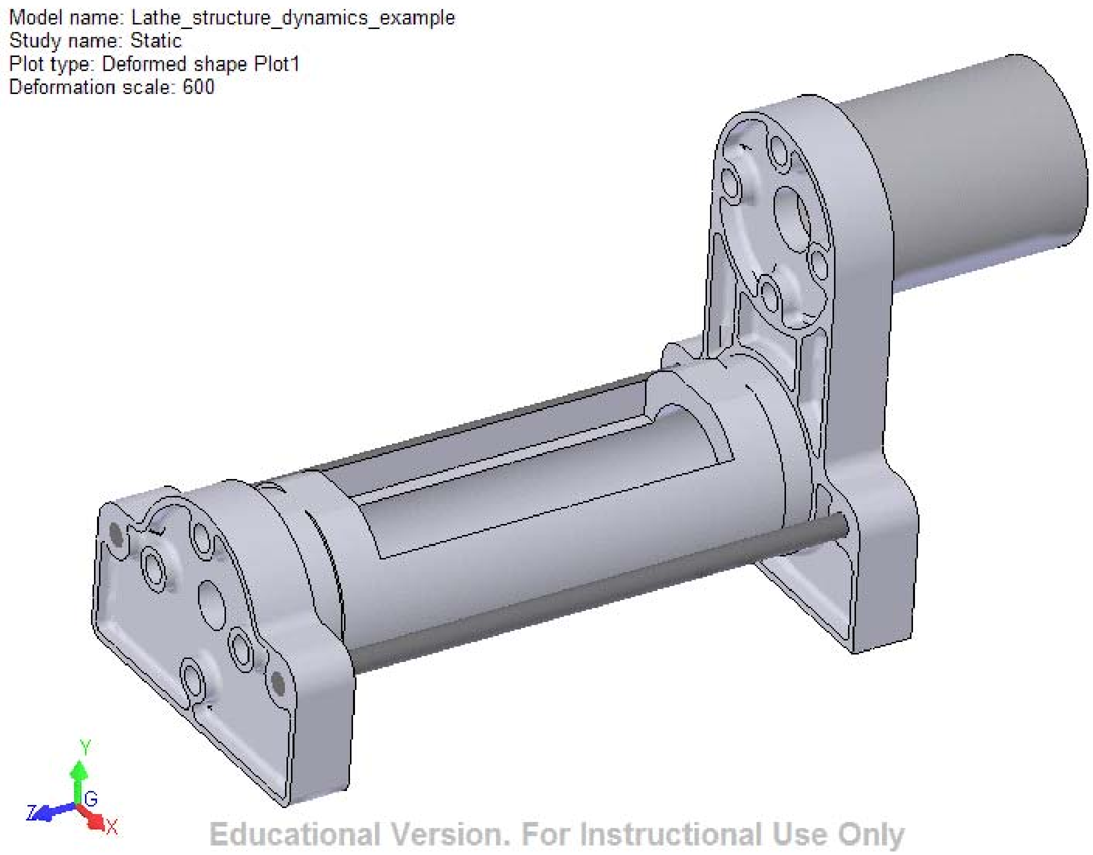
Static: Head stock deformation

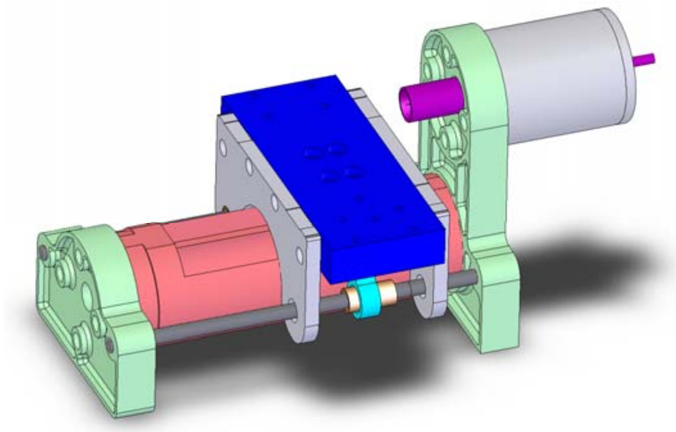


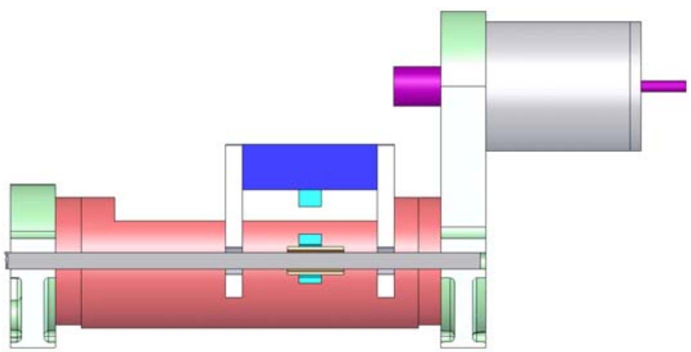




Static: Rail deformation







Example 1: $0 < x < a$

Cantilever

- Forces, moments, & torques

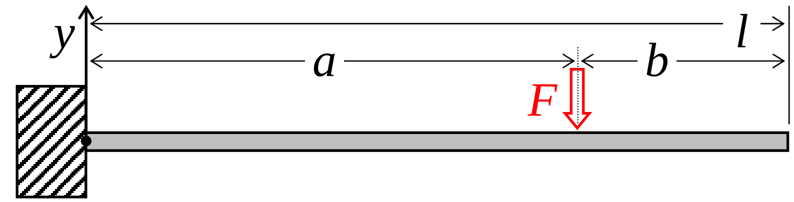
Why do we care?: Stress

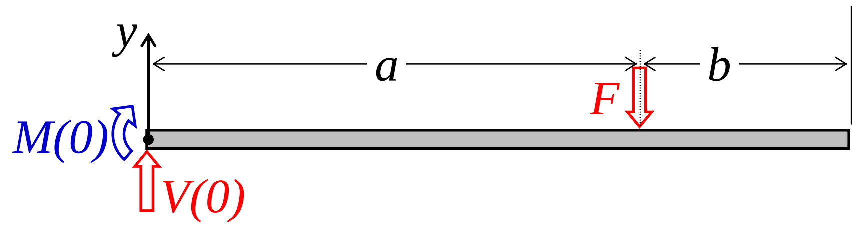
- Shear & normal
- Static failure
- Fatigue failure

Why do we care?: Stiffness

- Displacement
- Rotation
- Vibration → $({}^{k}/_{m})^{½}$

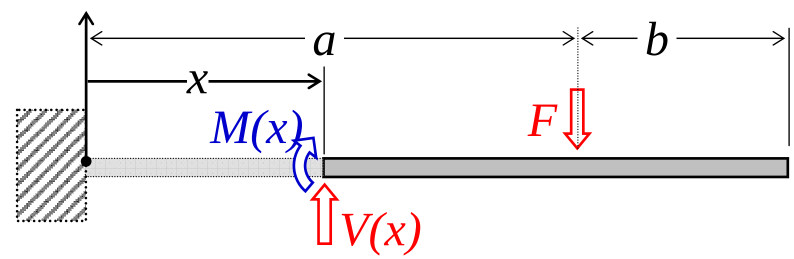
But, ends aren't all that matters





$$+\uparrow \Sigma \vec{F} = 0 = -F + V(0) \rightarrow V(0) = V(x) = F$$

$$\circlearrowleft + \Sigma \vec{M} = 0 = +F \cdot l + M(0) \rightarrow M(0) = -F \cdot a$$



$$+\uparrow \Sigma \vec{F} = 0 = -F + V(0) \rightarrow V(0) = V(x) = F$$

$$\circlearrowleft + \quad \Sigma \vec{M} = 0 = +F \cdot (a - x) + M(x) \rightarrow M(x) = -F \cdot (a - x)$$

Example 1: $0 < x < a$

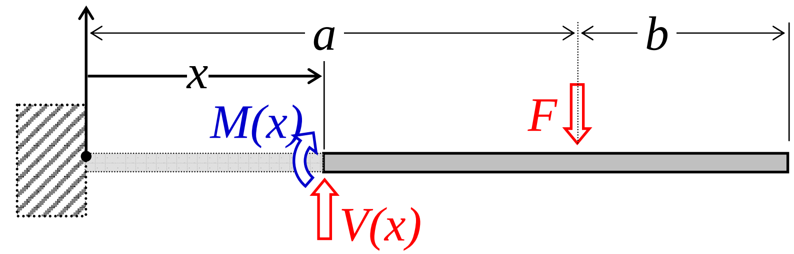
But, ends aren't all that matters

Relating V(x) & M(x)

- $\boxed{V(x) = F}$
- $\boxed{M(x) = F\cdot(x-a)}$
- $V(x) = \dfrac{d}{dx}M(x)$

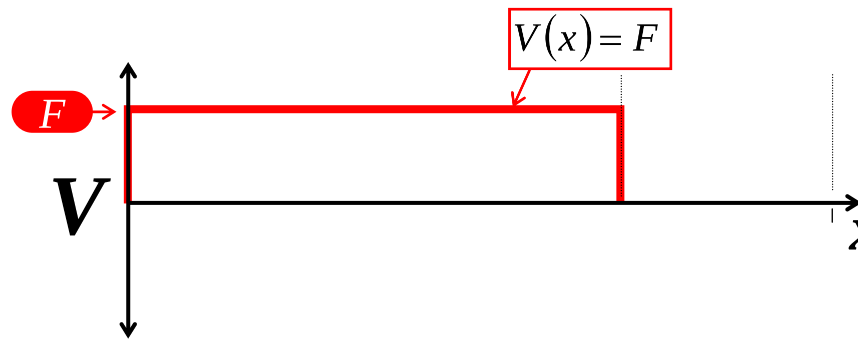
Shear moment diagrams

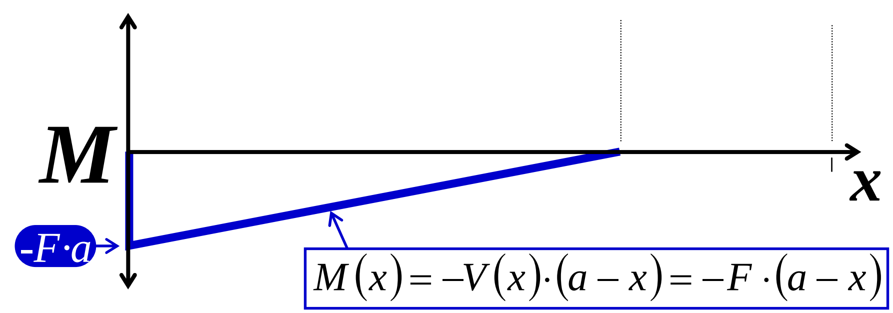
- Solve statics equation
- Put point of import on plots
- Use V=dM/dx to generate M plot
- Master before spindle materials



$$+\uparrow\sum\vec{F} = 0 = -F + V(0) \rightarrow V(0) = V(x) = F$$

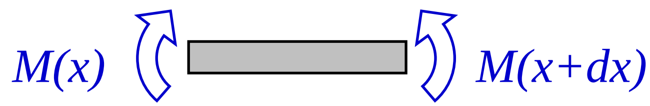
$$\circlearrowleft+\sum\vec{M} = 0 = +F\cdot(a-x) + M(x) \rightarrow M(x) = -V(x)\cdot(a-x)$$

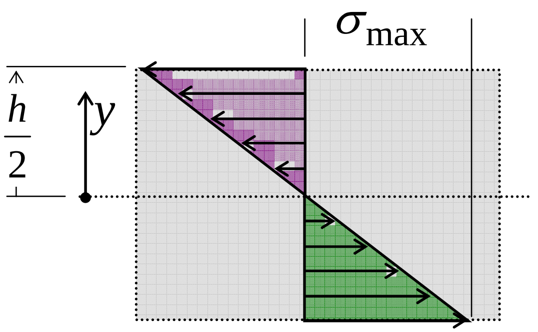


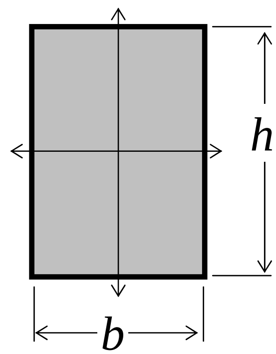


Example 1: $0 < x < a$

Stress





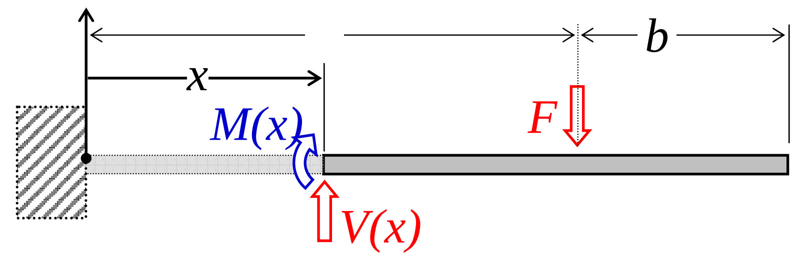


$$I(x) = \frac{1}{12}\; b(x)\; [h(x)]^3$$

$$\sigma(y) = M\,\frac{y}{I(x)} \rightarrow \sigma_{max} = M\,\frac{c}{I(x)}$$

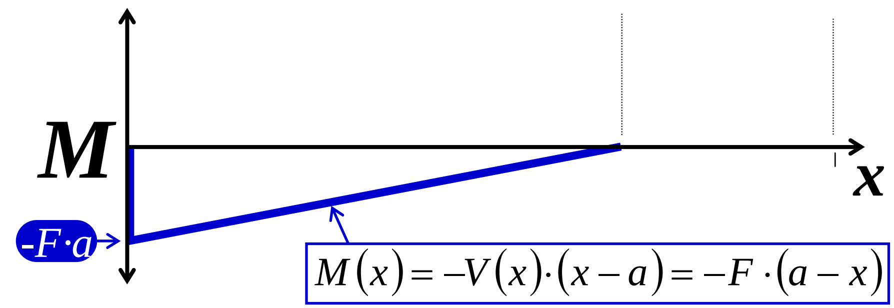
$$|\sigma_{max}| = F\cdot(a-x)\frac{h(x)}{2}\,\frac{12}{b(x)\cdot[h(x)]^3}$$

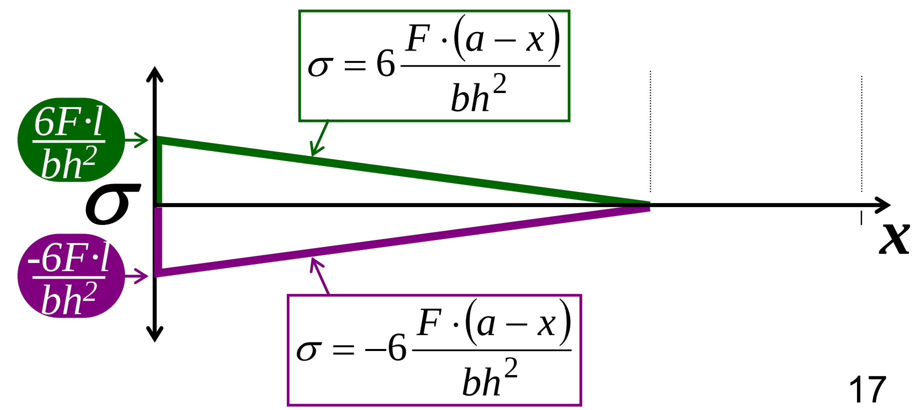
$$|\sigma_{max}| = 6\,\frac{F\cdot(a-x)}{b(x)\cdot[h(x)]^2}$$



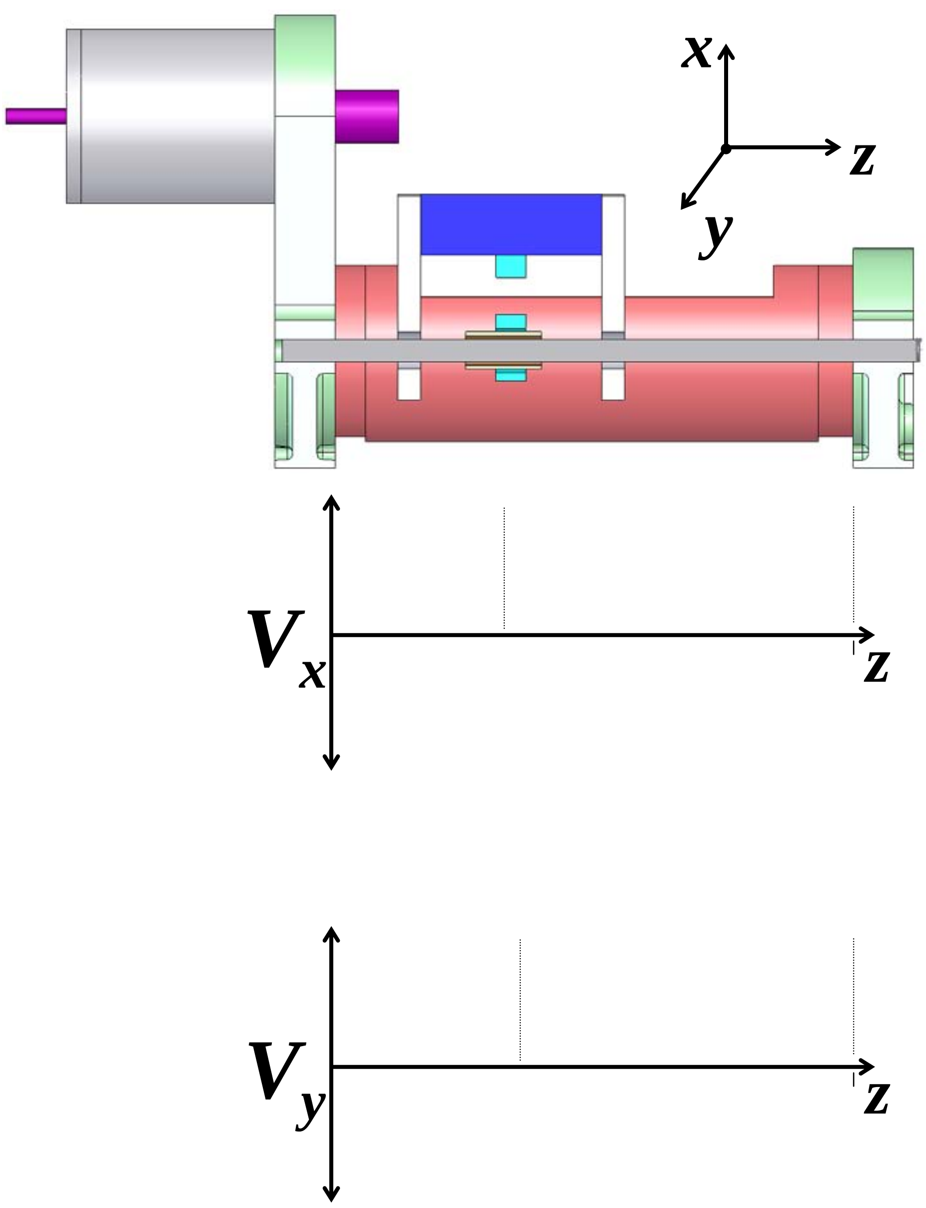
$$+\!\uparrow \Sigma\vec{F} = 0 = -F + V(0) \rightarrow V(0) = V(x) = F$$

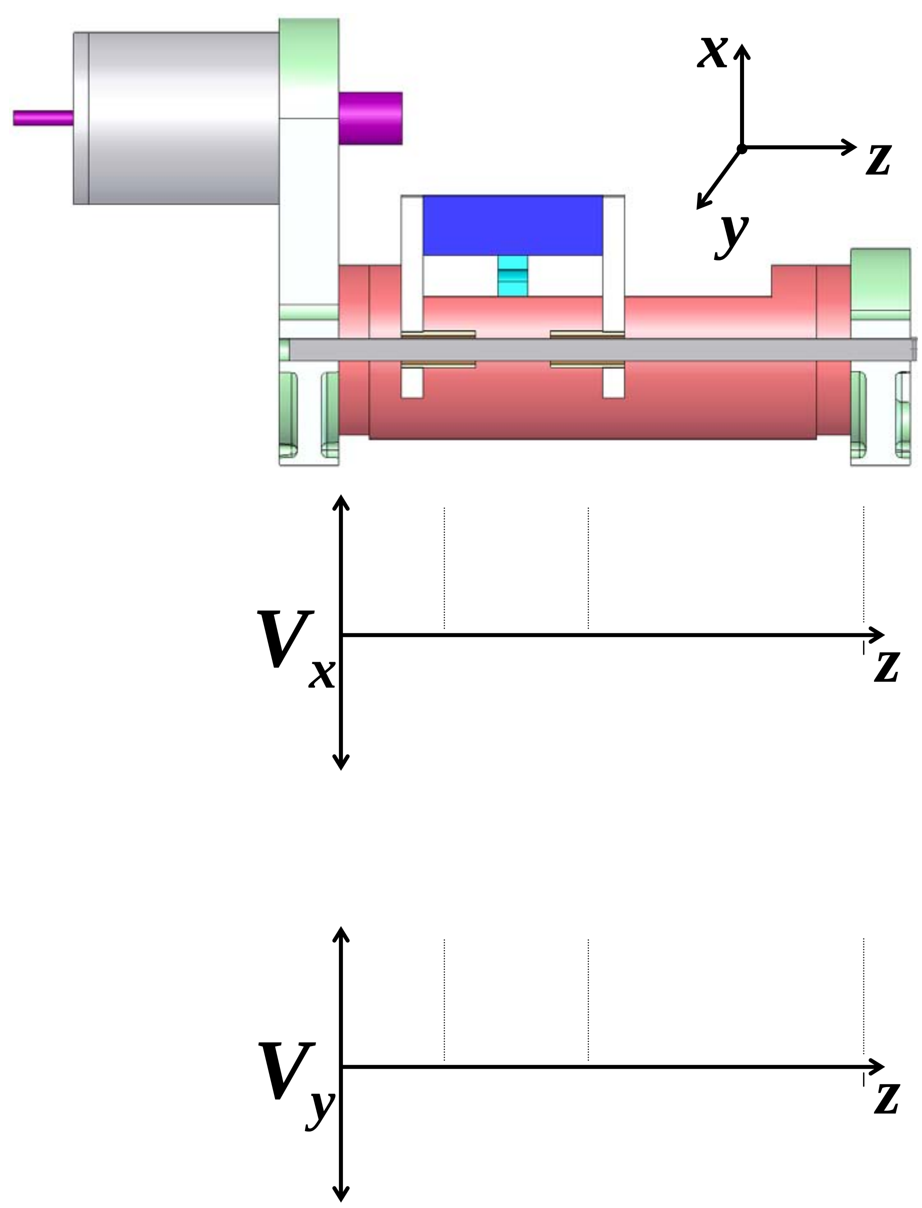
$$+\!\circlearrowleft \Sigma\vec{M} = 0 = +V(x)\cdot(a-x) - M(x) \rightarrow M(x) = -V(x)\cdot(a-x)$$





Group work: Generate strategy for this…





Dynamics

Vibration

Vibration principles

- Exchange potential-kinetic energy
- 2nd order system model

Blocks and squiggles…

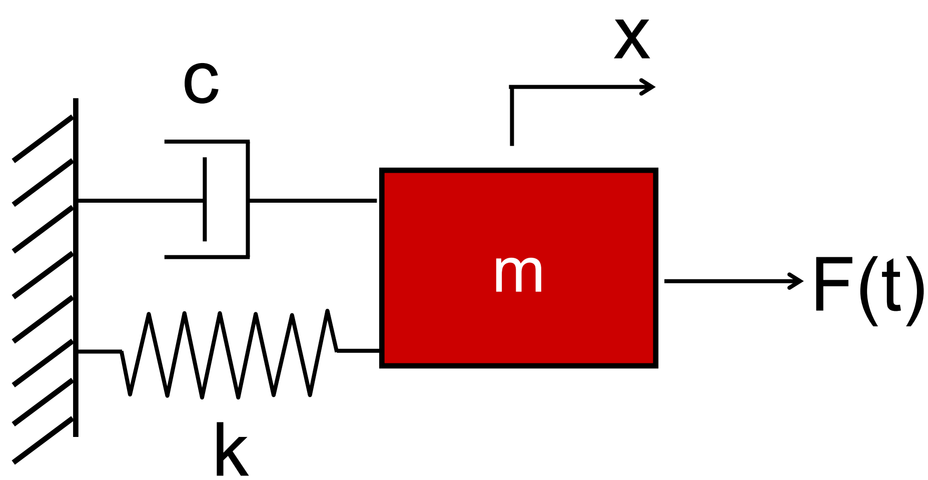
- What do they really mean?
- Why are they important?
- How will we apply this?

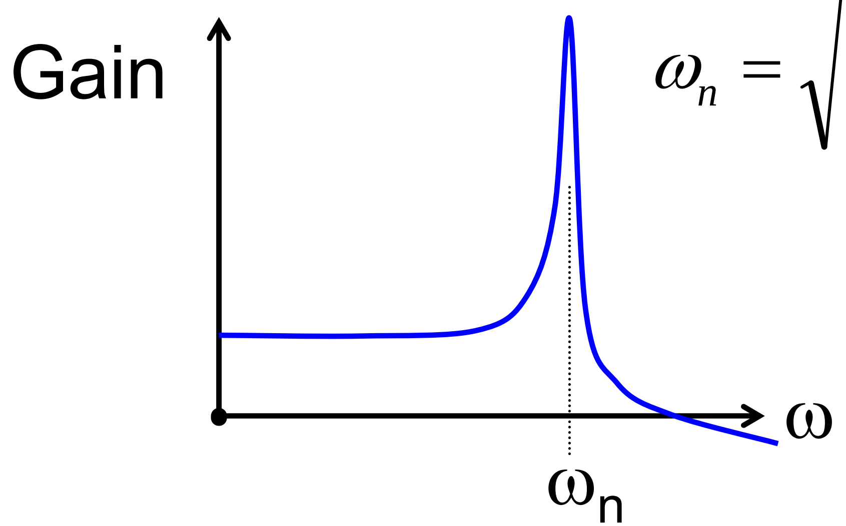
Multi-degree-of-freedom system

- Mode shape
- Resonant frequency

Estimate ω_n (watch units) for:

- A car suspension system





$$\omega_n = \sqrt{\frac{k}{m}}$$

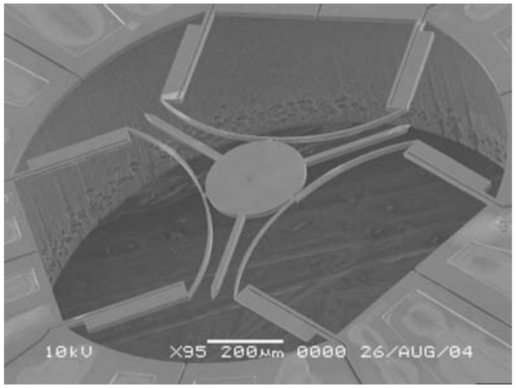
Images removed due to copyright restrictions. Please see:

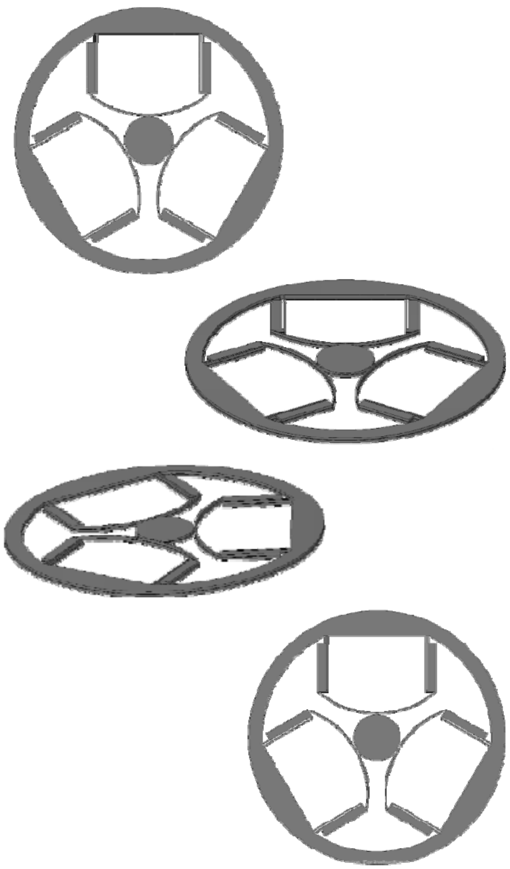
http://www.hpiracing.com/graphics/kits/547/_MG_1962e.jpg

http://www.societyofrobots.com/images/mechanics_suspension_honda.gif

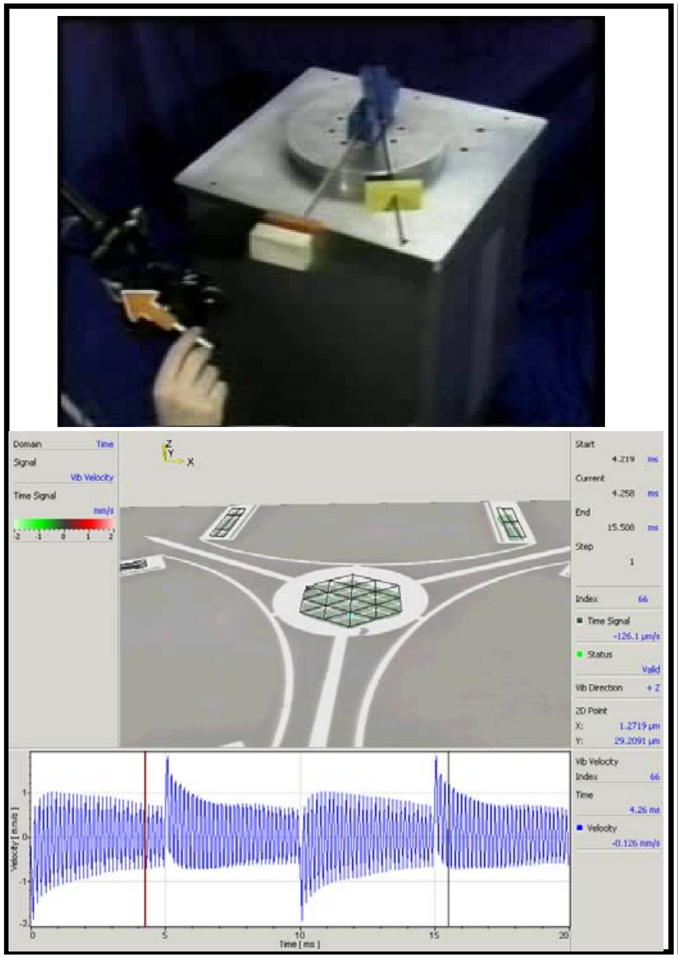
http://www.bose.com/images/learning/lc_susp_frontmodule.jpg

Vibration: MEMS device behavior

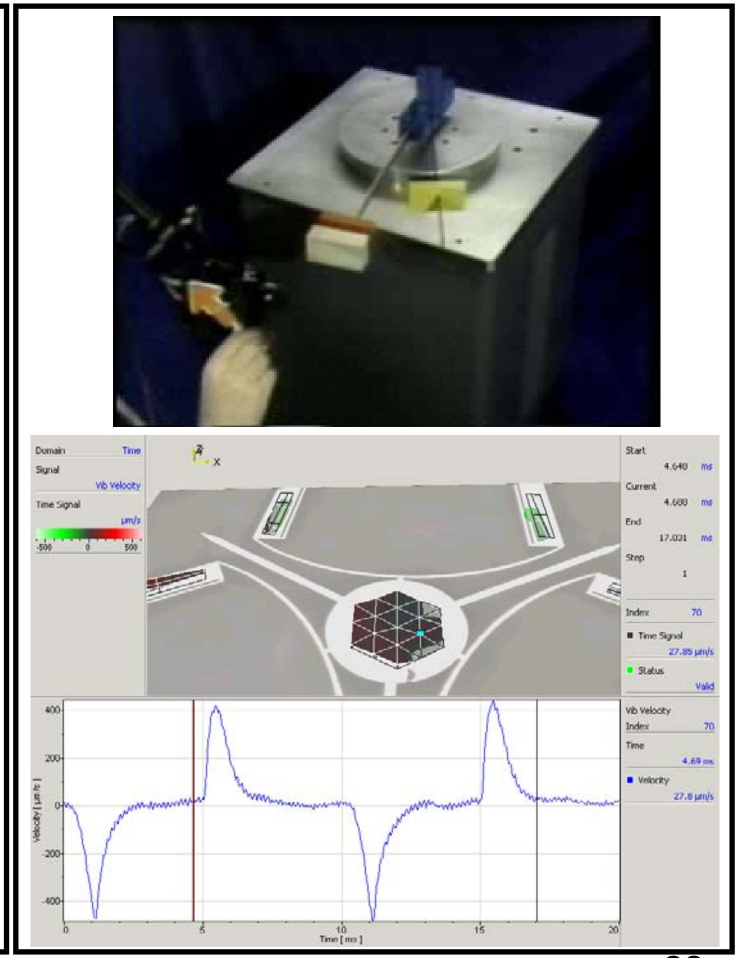




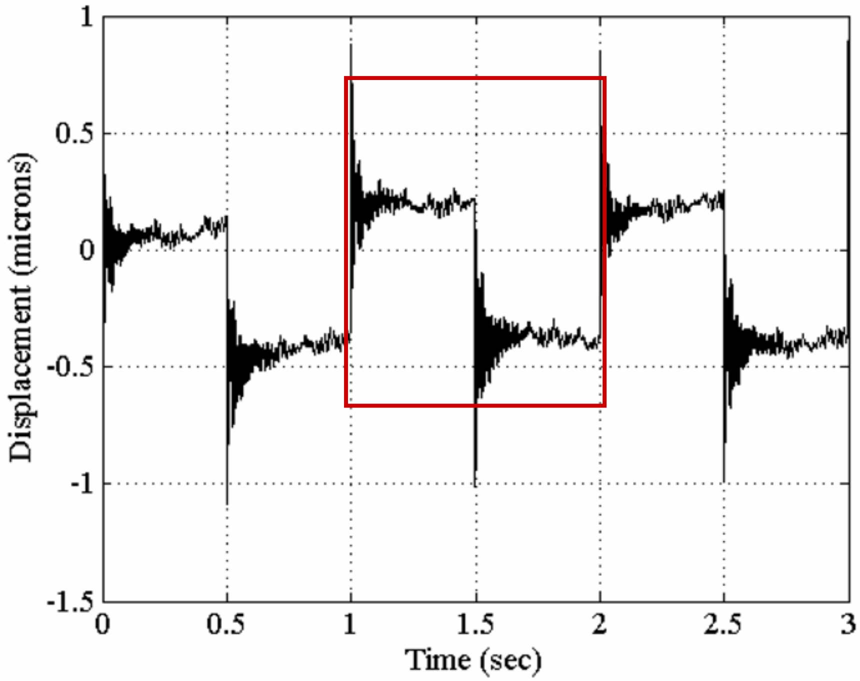
Without input shaping



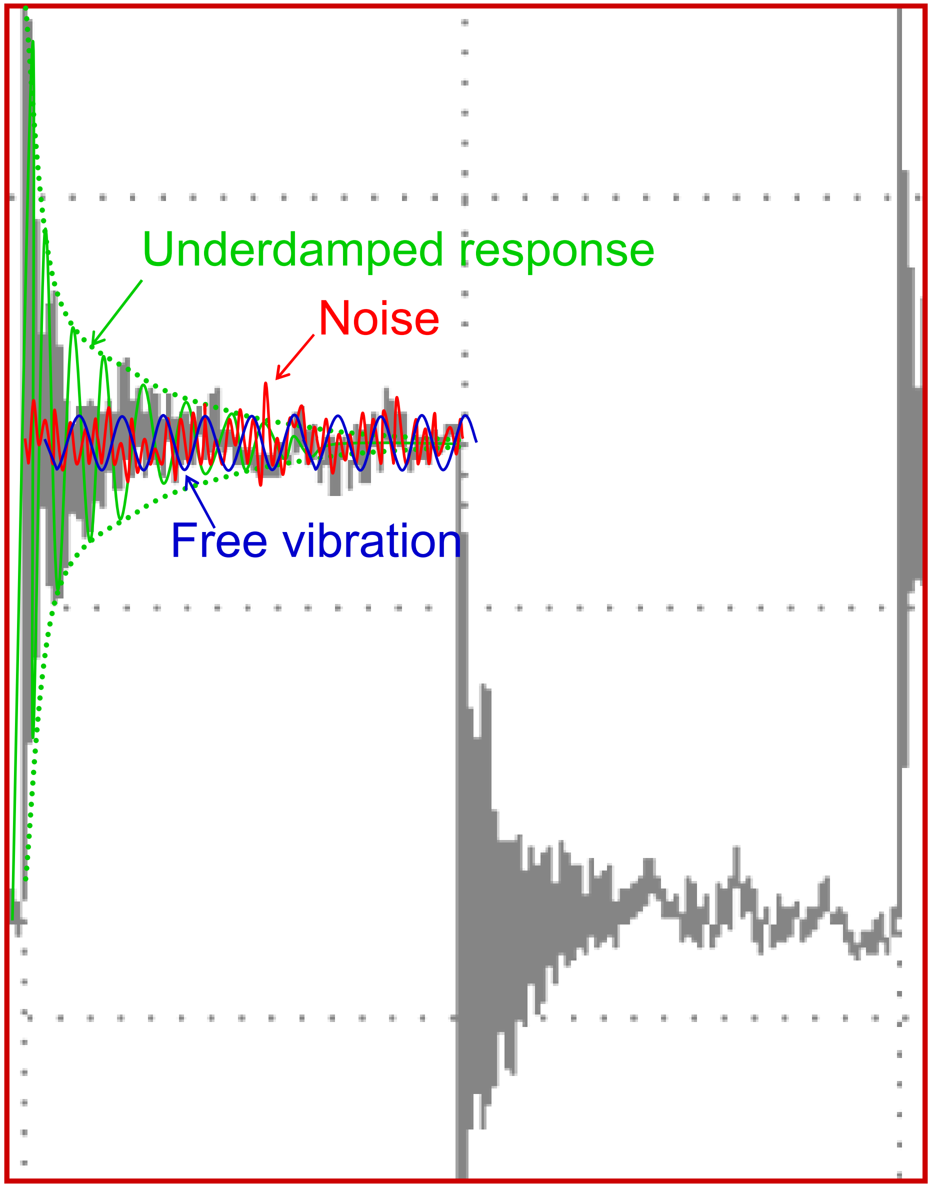
With input shaping



Vibrations: Meso-scale device behavior

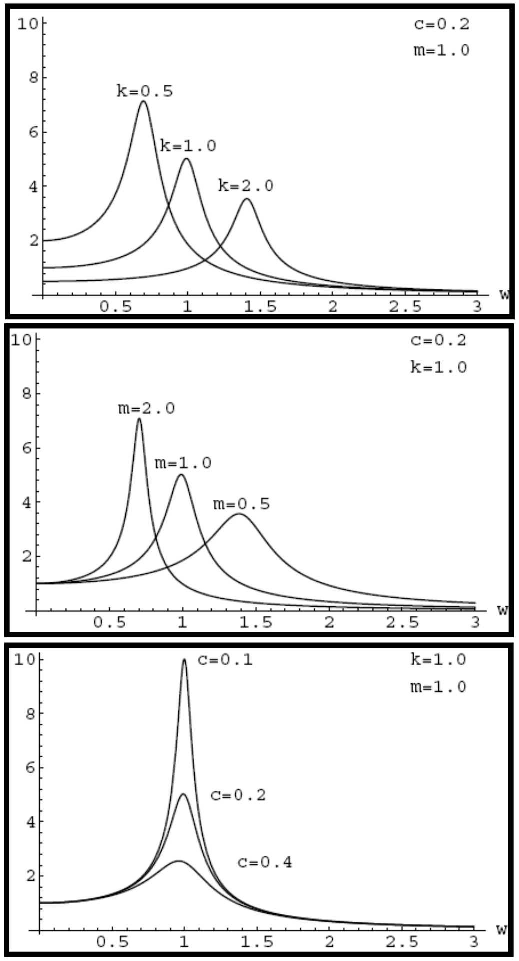


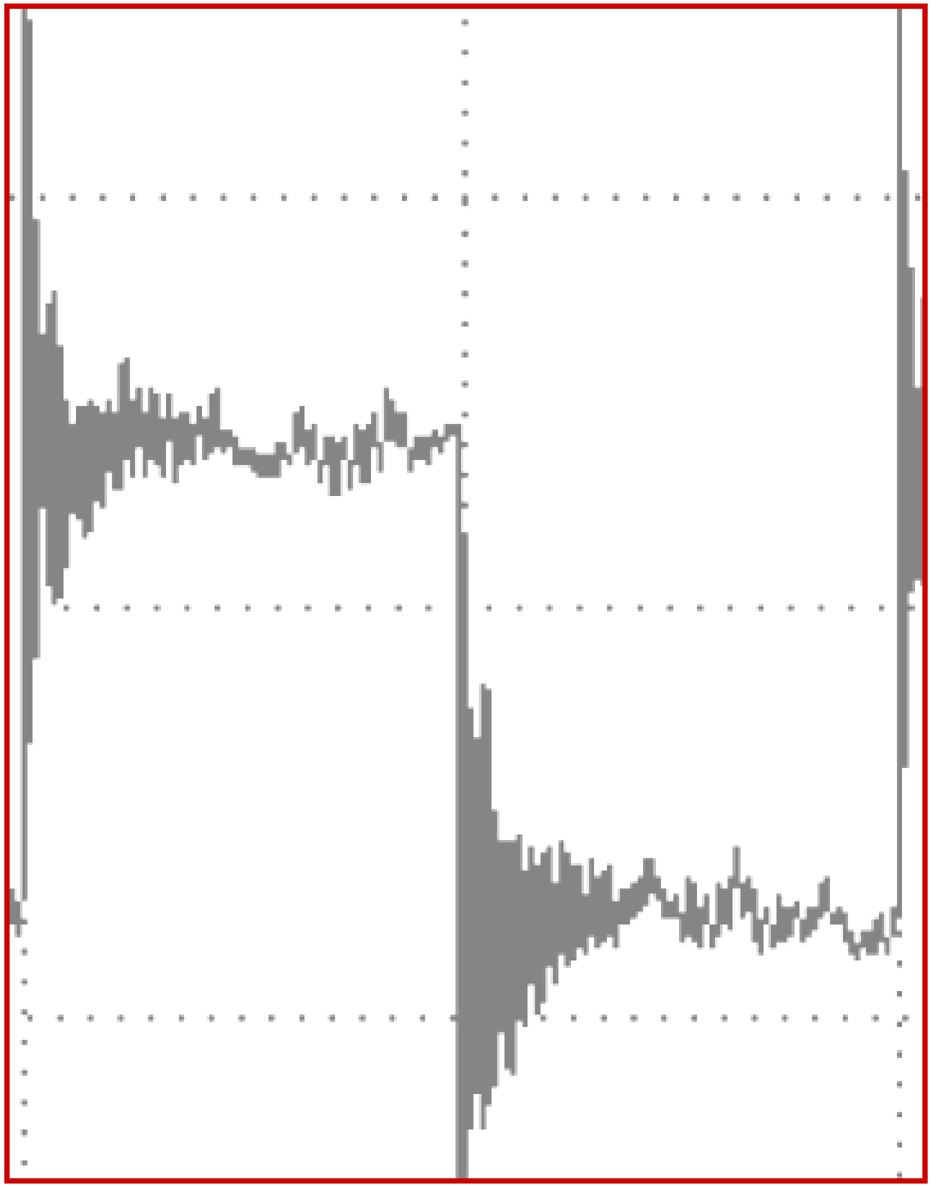
Golda, D. S., "Design of High-Speed, Meso-Scale Nanopositioners Driven by Electromagnetic Actuators," Ph.D. Thesis, Massachusetts Institute of Technology, ***2008***.



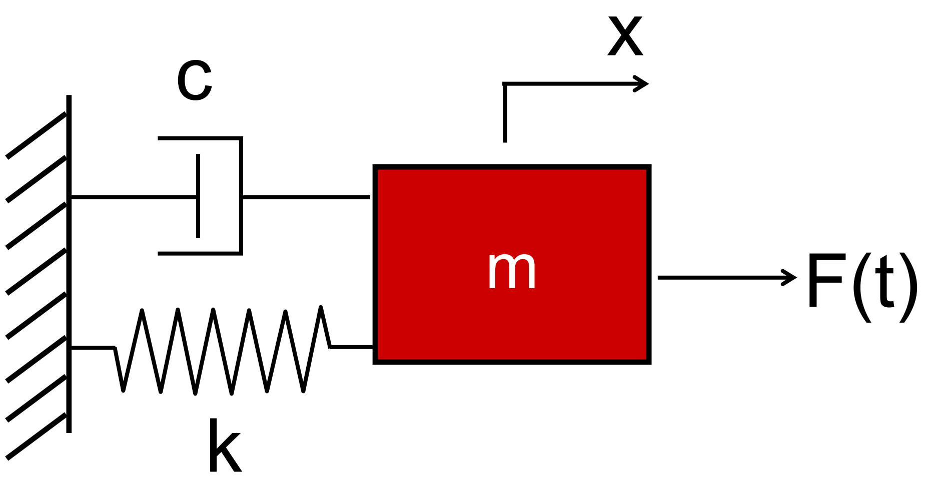
Vibrations: Reducing amplitude…

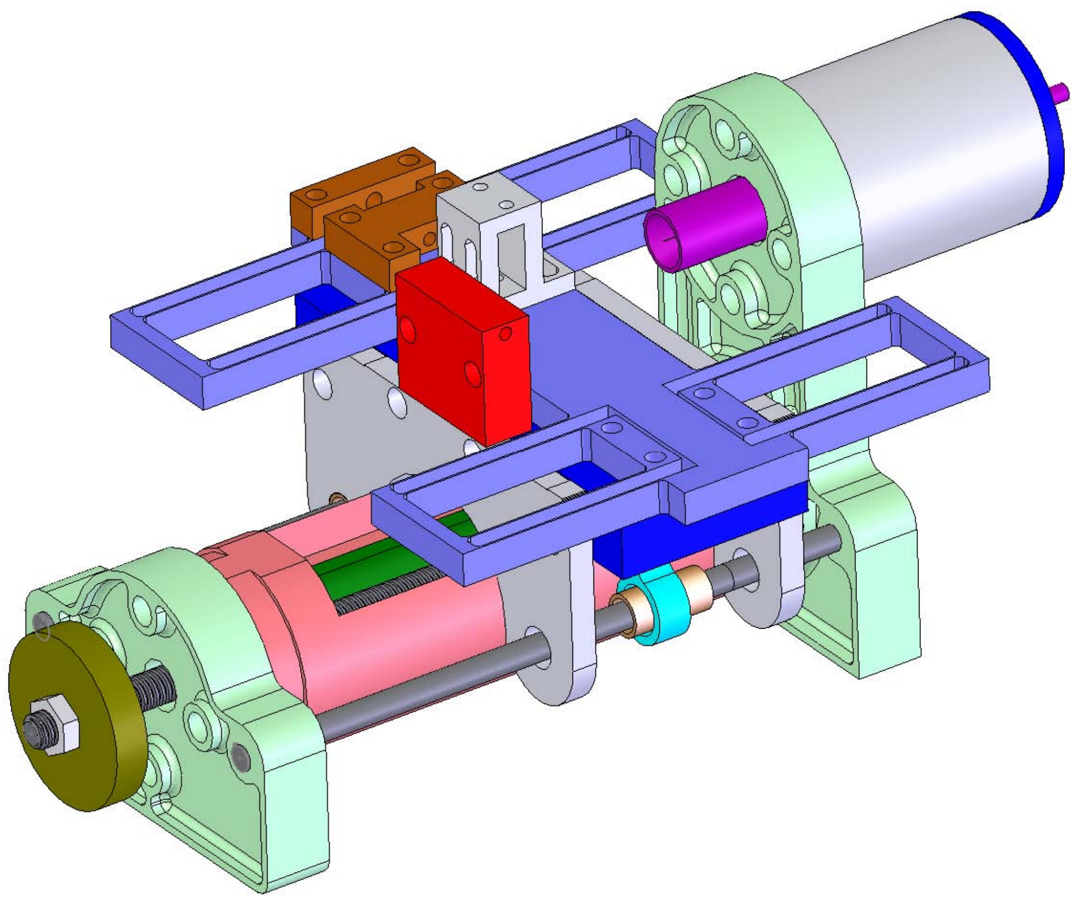
How to change
m, k, and c?



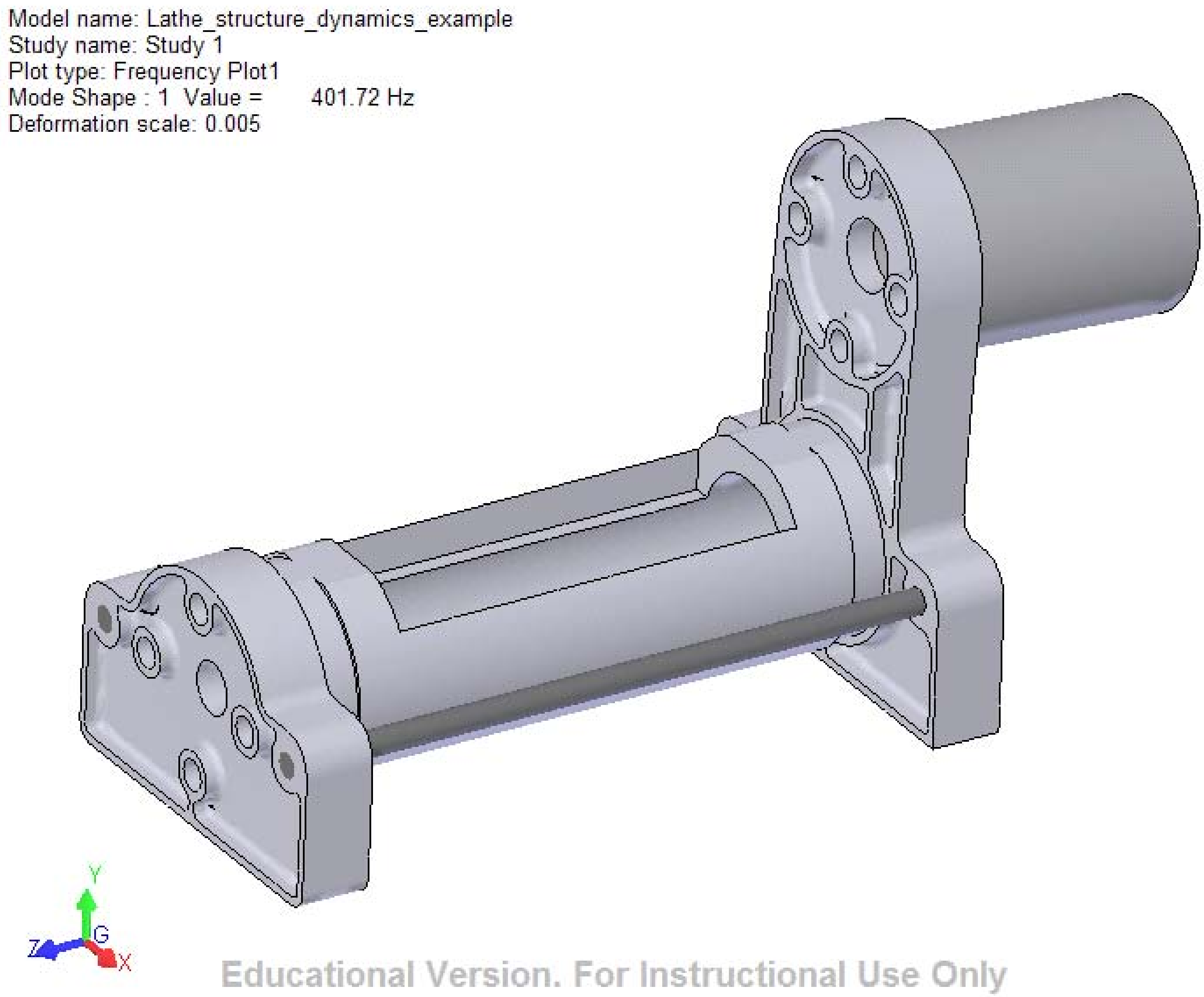


So… where find in reality… in lathe…

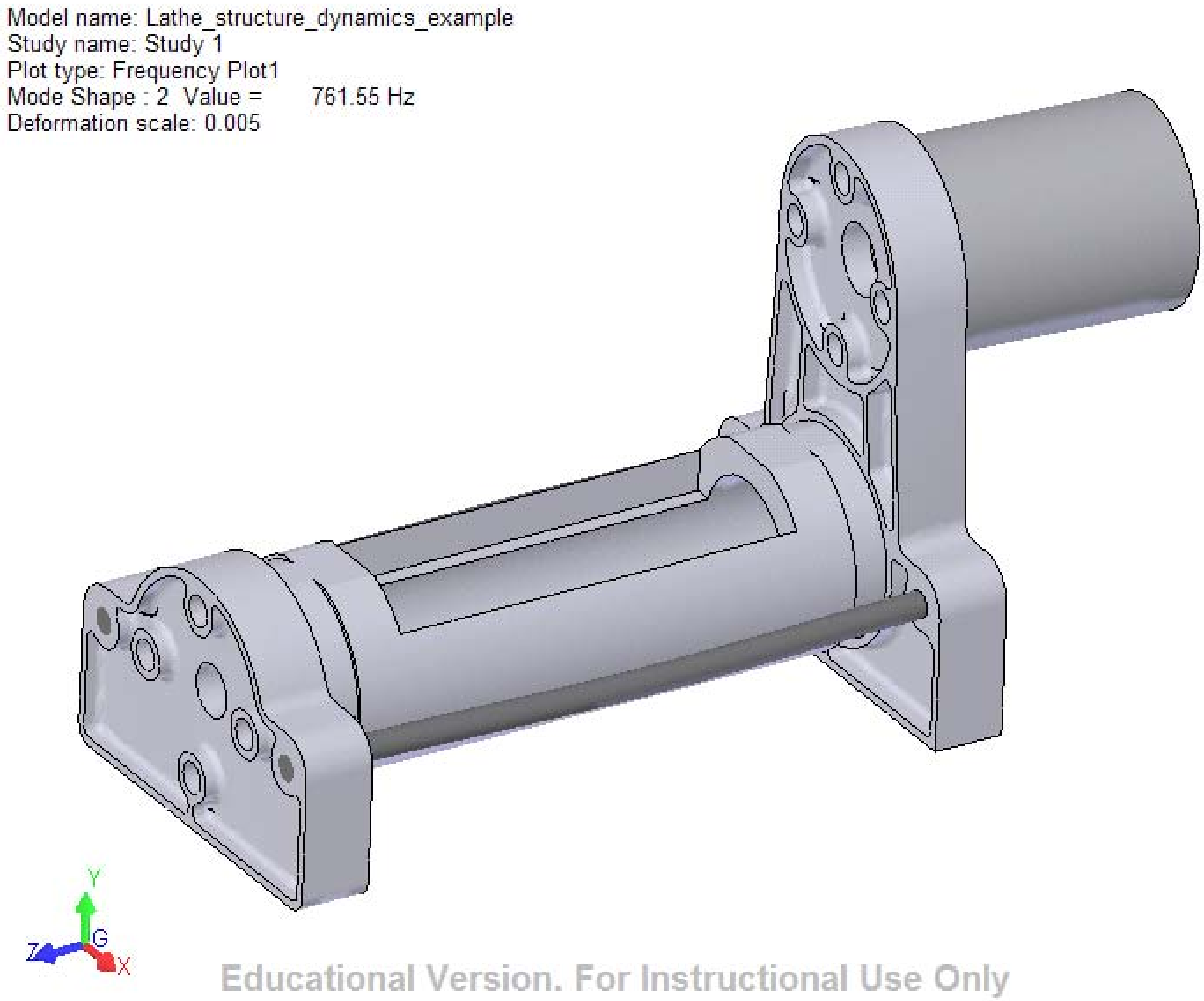




Vibration: Lathe structure – 1st mode



Vibration: Lathe structure – 2nd mode



Heat transfer

Thermal growth errors

For uniform temperature

$$\Delta L = \alpha \; L_o \; \Delta T$$

$$STEEL: 12L14 \rightarrow \Delta L = 11.5 \times 10^{-6} \frac{m}{m\,^oC} L_o \; \Delta T$$

$$ALUMINUM: 6061\,T6 \rightarrow \Delta L = 23.6 \times 10^{-6} \frac{m}{m\,^oC} L_o \; \Delta T$$

$$POLYMER: Delrin \rightarrow \Delta L = 100 \times 10^{-6} \frac{m}{m\,^oC} L_o \; \Delta T$$

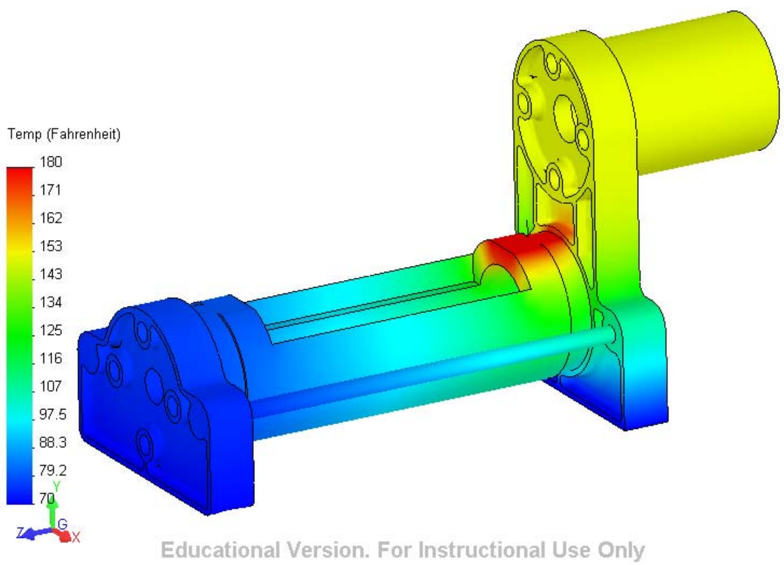
Convection and conduction

Convection:

$$\dot{q} = h\,A_{surface}\left(T - T_{\infty}\right)$$

Why do we care?

- Heat removal from cutting zone
- Heat generation in bearings
- Thermal growth errors



Conduction:

$$\dot{q} = k\,A_{cross}\,\frac{dT}{dx}$$

Why do we care?

- Heat removal from cutting zone
- Heat generation in bearings
- Thermal growth errors

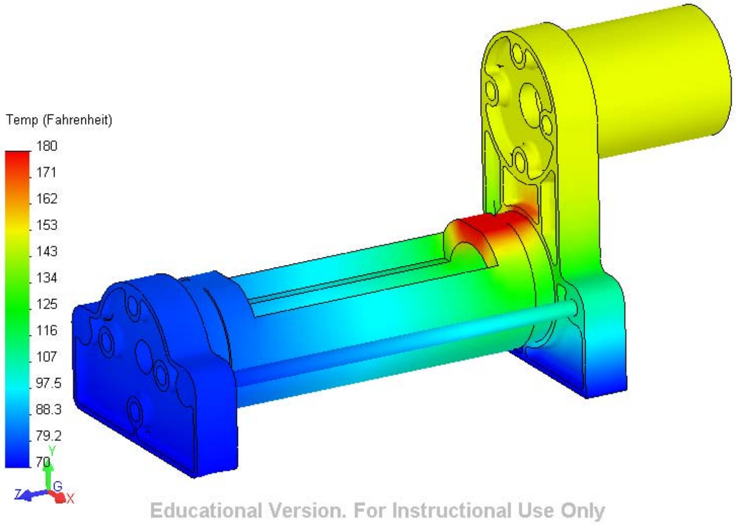
Common k values to remember

- Air 0.026 W /(m^{o}C)
- 12L14 51.9 W /(m^{o}C)
- 6061 T6 167 W /(m^{o}C)

Thermal resistance

Thermal resistance

$$\dot{q} = \frac{\Delta T}{R_T}$$



- Convection

$$\dot{q} = \frac{(T - T_\infty)}{(h\,A_{surface})^{-1}} \mapsto R_T = \frac{1}{h\,A_{surface}}$$

- Conduction

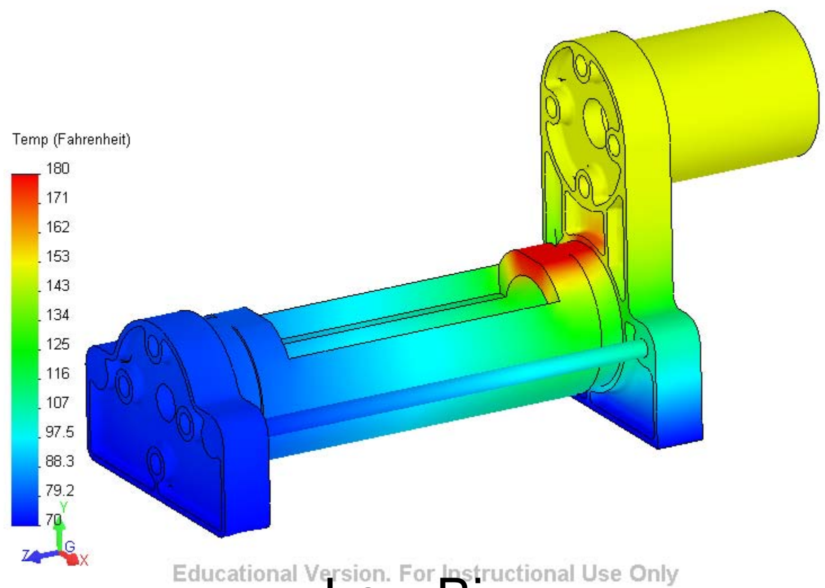
$$\dot{q} = dT\,\frac{k\,A_{cross}}{dx} \mapsto R_T = \frac{dx}{k\,A_{cross}}$$

Biot (Bi) number

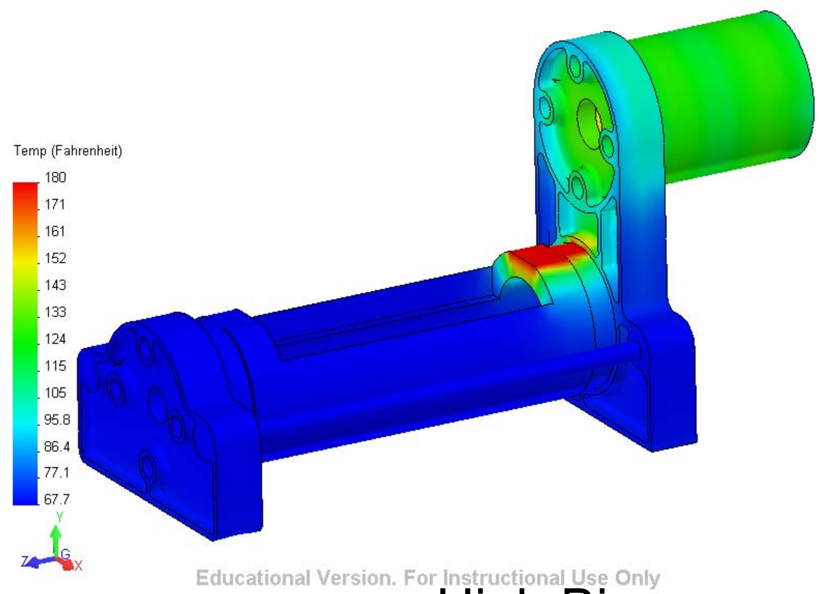
Ratio of convective to conductive heat transfer

$$\frac{\dot{q}_{convection}}{\dot{q}_{conduction}} \mapsto \frac{\left(h\,A\,\Delta T\right)\big|_{convection}}{\left(k\,A\,\dfrac{\Delta T}{L}\right)\Big|_{conduction}} \mapsto Bi = \frac{hL_c}{k}$$

Why do we care?



Low Bi

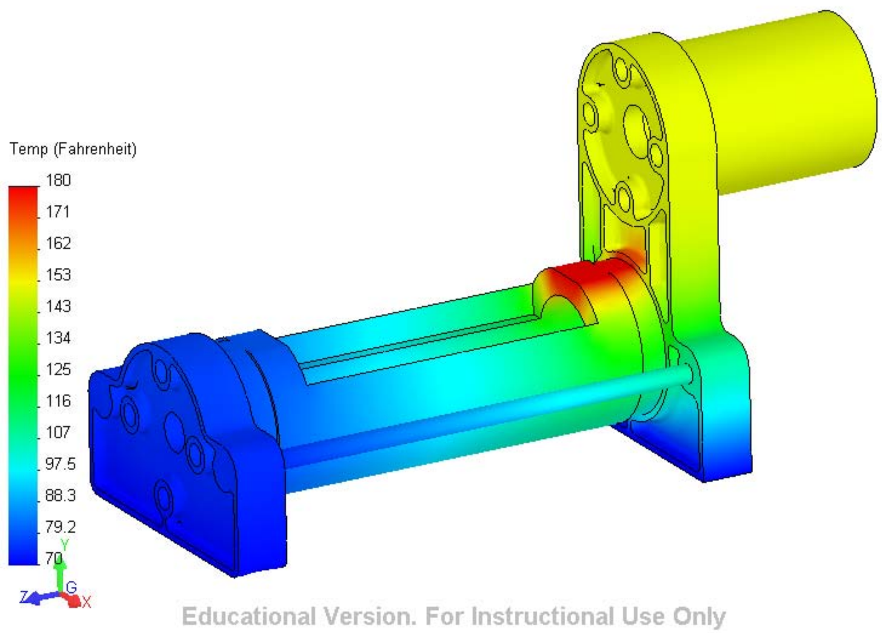


High Bi

Example of thermal errors

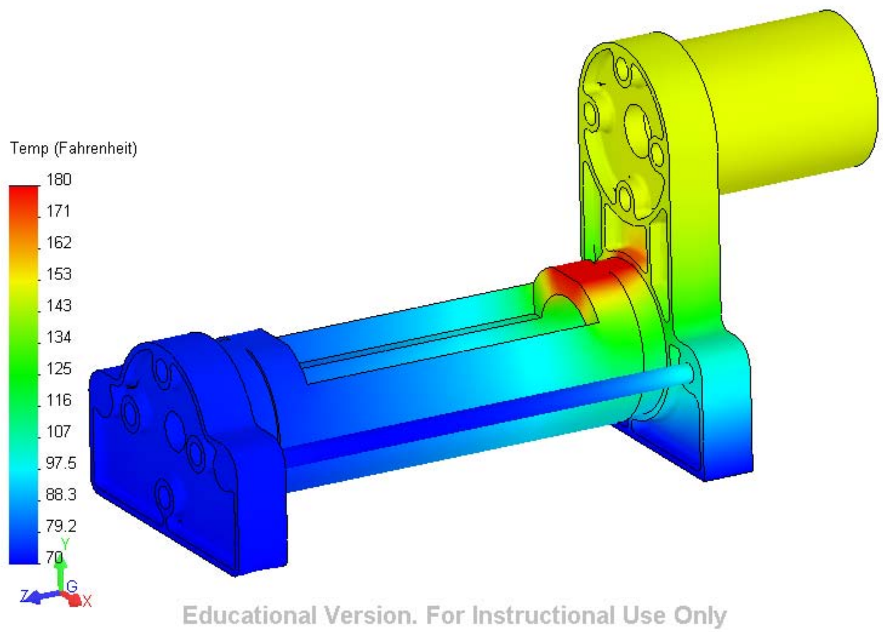
For:

- h = 0.1 $W/(m^2 {}^oC)$
- Bearing T = 150 ^oF
- Chip T = 180 ^oF



For:

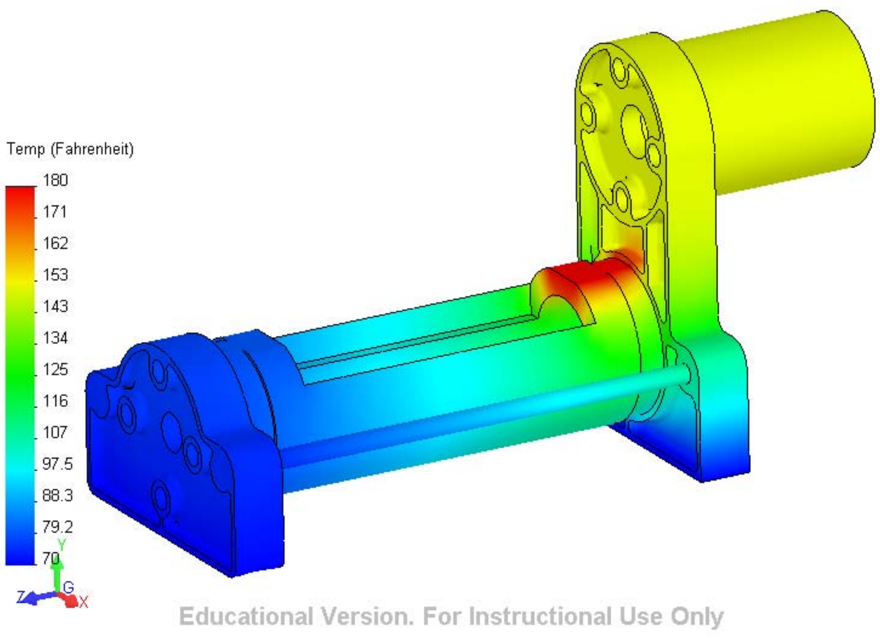
- h = 50 $W/(m^2 {}^oC)$
- Bearing T = 150 ^oF
- Chip T = 180 ^oF



Example of thermal errors

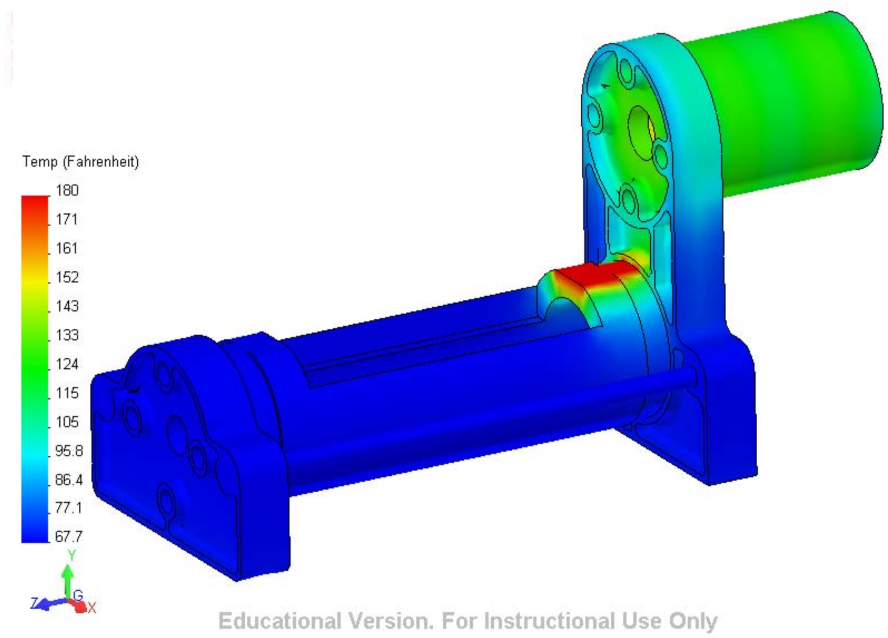
For:

- h = 0.1 W/(m^2°C)
- Bearing T = 150 °F
- Chip T = 180 °F



For:

- h = 5000 W/(m^2°C)
- Bearing T = 150 °F
- Chip T = 180 °F



Types of errors

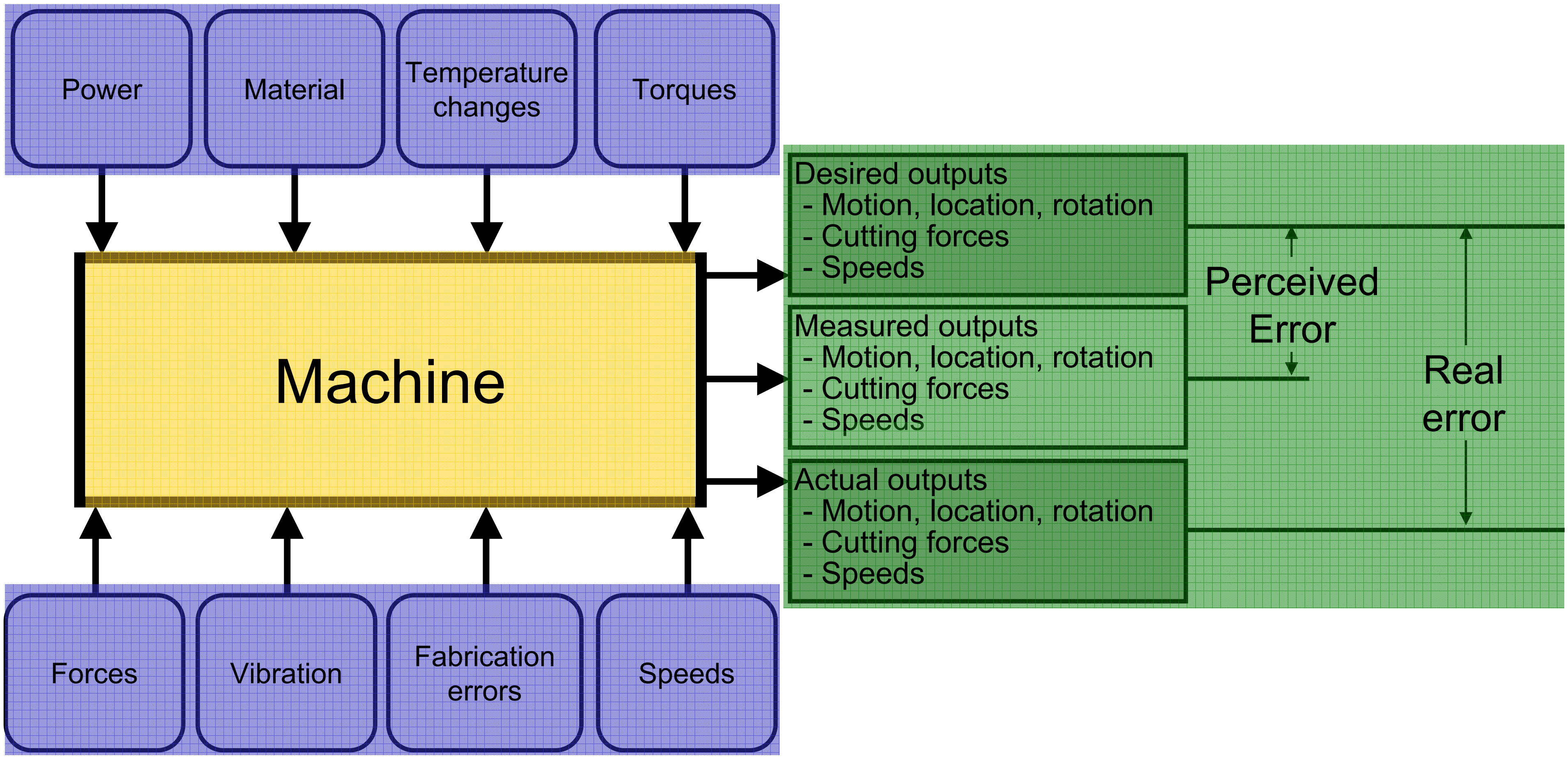
Machine system perspective

System-level approach

Linking inputs and outputs

Measurement quality

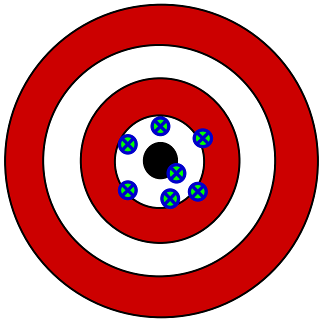
$$[Outputs] = \begin{bmatrix} C_1 & C_2 & C_3 \\ C_4 & C_5 & C_6 \\ C_7 & C_8 & C_9 \end{bmatrix} [Inputs]$$



Errors….

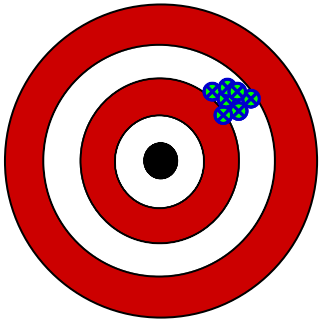
Accuracy

- The ability to tell the "truth"



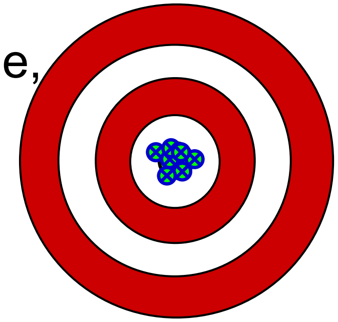
Repeatability

- Ability to do the same thing over & over



Both

- 1st make repeatable, then make accurate
- Calibrate



Determinism

- Machines obey physics!
- Model → understand relationships

$$[Outputs] = \begin{bmatrix} C_1 & C_2 & C_3 \\ C_4 & C_5 & C_6 \\ C_7 & C_8 & C_9 \end{bmatrix} [Inputs]$$

- Understand sensitivity

$$[\Delta Outputs] = J\,[\Delta Inputs]$$

Range

- Furthest extents of motion

Resolution

- Smallest, reliable position change

Categorizing error types

Systematic errors

- Inherent to the system, repeatable and may be calibrated out.

Non-systematic errors

- Errors that are **perceived and/or modeled** to have a statistical nature
- Machines are not “random,” there is no such thing as a random error

Consider the error for each set below

- Link behavior with systematic and non-systematic errors.

Exercise

Exercise

Due Tuesday, start of class:

Lathe components

- Rough sketch(es) of lathe
- Annotate main components

1 page bullet point summary of where need to use:

- 2.001, 2.002 2.003, 2.004 2.005, 2.006 2.007, 2.008

Rules:

- You may not re-use examples from lecture!
- You are encouraged to ask any question!
- You may work in groups, but must submit your own work

Group work: Generate strategy for this…