Prototyping in Mechanical Engineering

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Class 5: Motion

Movie Break!

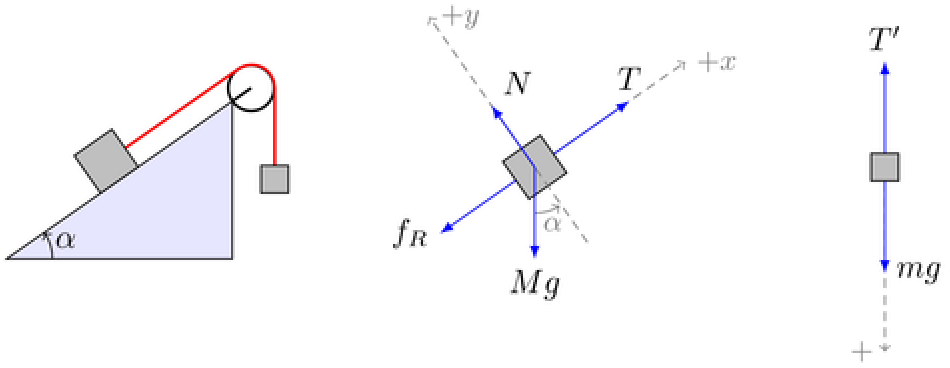
Today's Agenda

- ~~Movie Break!~~
- Intro to Motion
- Power Transmission
- Linear Actuation
- Rotary Actuation

Intro to Motion

Introduction

- What is Motion?
  - Things (with mass) moving (from one place to another)
- Newton's Laws:
  - Inertia
  - F = ma
  - Opposing forces
- Today's class:
  - A warming blend of practical and theoretical



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Newton's Second Law

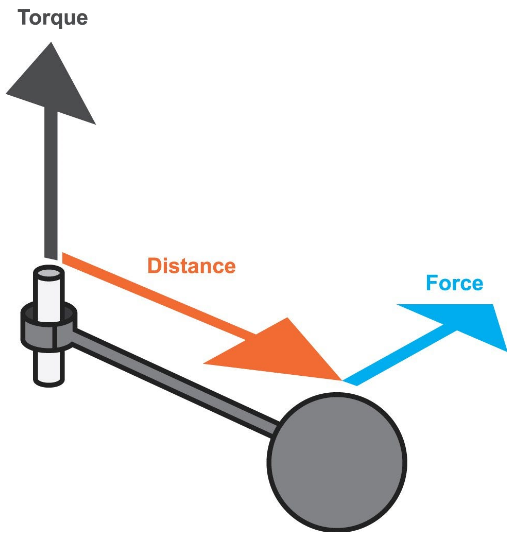
Force = Mass * Acceleration

Force

$$\mathbf{N} = kg \cdot \left(\frac{m}{s^2}\right)$$

Torque

- Torque is the rotational equivalent of Force
  - Torque = Force * Moment Arm
  - Torque is measured in Newton-meters (Nm)



Work

Work = Force * Distance

Work

Joule (unit) = $\mathrm{N} \cdot m$

Work

$$\mathrm{J} = kg \cdot \left(\frac{m^2}{s^2}\right)$$

Energy

- Energy and Work use the same units:
  - Joules
- Energy can be used to do work
- Energy also measures losses to heat
- Energy is conserved
  - Energy in = Energy out
  - Work in = Work out + heat
- Efficiency
  - $\eta = \frac{(Useful)\ Energy\ out}{Energy\ in}$

Energy, another way to calculate

- Kinetic energy

$$KE = \frac{1}{2}mv^2$$

- Potential energy
  - Gravitational

$$PE = mgh$$

  - Mechanical (springs)

$$PE = \frac{1}{2}kx^2$$

  - Chemical
  - Others

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Energy Example

$$PE_{spring} = KE_{launch} = PE_{gravitational}$$

$$\frac{1}{2}kx^2 = \frac{1}{2}mv^2 = mgh$$

$$\frac{1}{2}(12)(0.5)^2 = \frac{1}{2}(1)v^2 = (1)(9.81)h$$

$$\frac{1}{2}(12)(0.5)^2 = 1.5\,J = \frac{1}{2}(1)v^2 = (1)(9.81)h$$

$$v = \sqrt{3} \approx 1.73\,\frac{m}{s}$$

$$h = \frac{1.5}{9.81} = 0.15\,m$$

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Power

Power = Work / Time

Power

Watt (unit) = J/s

Power

$$\text{Watt} = kg \cdot \left(\frac{m^2}{s^3}\right)$$

Gravity

- Gravity is an acceleration that acts on all things with mass:
  - Gravity (sea level) = 9.81 $\frac{m}{s^2}$

$$F_g = 9.81 * (m)$$

  - Work done to raise 10 kg one meter?

$$W_g = 9.81(10)(1) = 98.1\ J$$

  - Power required to raise 10kg one meter in 30 seconds?

$$\frac{9.81(10)(1)}{30} = 3.27\ W$$

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Gravity

- Do our units make sense?

$$\frac{9.81(10)(1)}{30} = 3.27\ W$$

  - Let's see:

$$\frac{\left(9.81\,\frac{m}{s^2}\right)(10\ kg)(1\ m)}{30\ s} = \frac{(9.81)(10)(1)\left(m^2\right)(kg)}{30\ s^3} = (3.27)\left(\frac{kg\ m^2}{s^3}\right) = 3.27\ W$$

  - Hooray!

Power Tradeoffs

Power = Work / Time

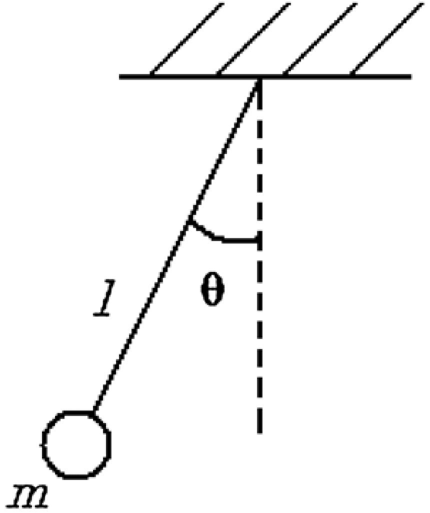
Power = Work / Time

Power = Work / Time

Power = Work / Time

Control & Stability

- Stability: The tendency to stay where you are
  - Like inertia!
- Control: The ability to change your system's state
  - Hates inertia!



Control & Stability

Power = Stability * Control

Power = Stability * Control

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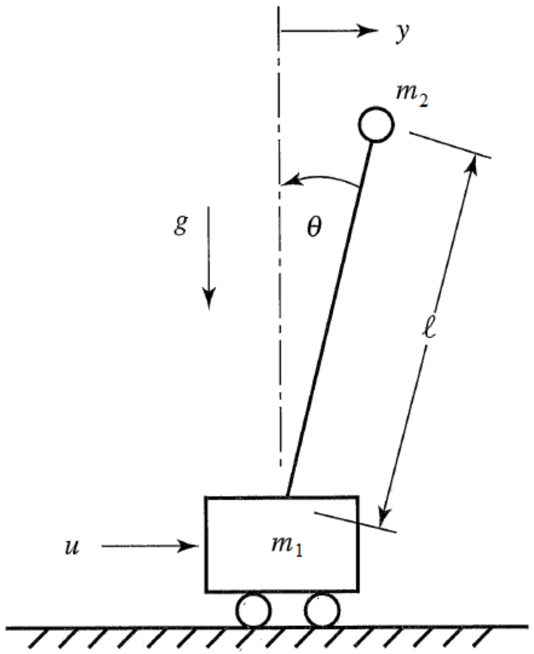
Power = Stability * Control

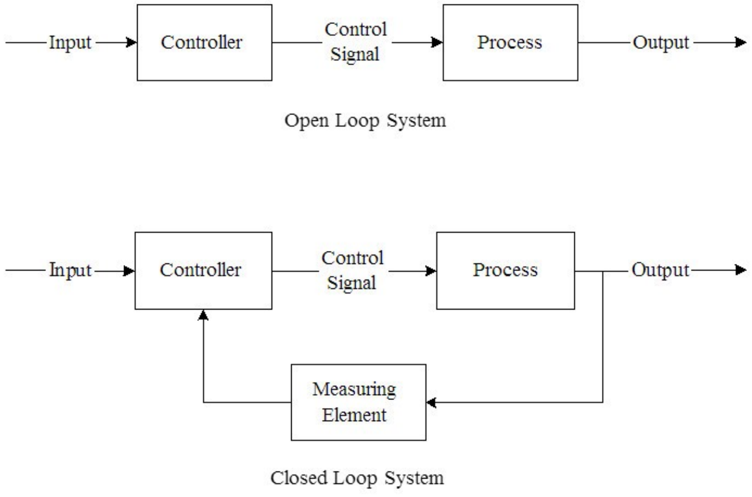
Control Systems

Movie Break!

Control Systems

- How do I get a thing to where I want it to be?
- State information (sensors)
- Output
- Open loop vs. closed loop





Degrees of Freedom

- Mechanical systems are often defined by their “Degrees of Freedom”
  - A free body has 6 DOF
    - 3 rotational
    - 3 translational
  - A motor is 1 DOF
    - 1 rotational
  - A slider is 1 DOF
    - 1 translational

Degrees of Freedom

Movie Break!

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Power Transmission

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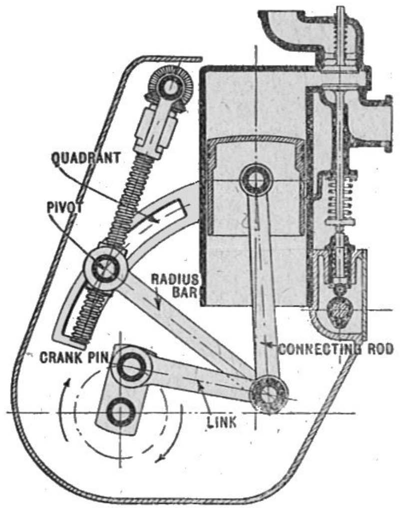
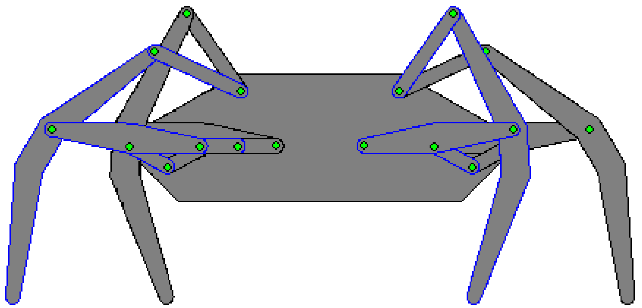
Power Transmission

- Types of power transmission
  - Linkages
  - Belts and pulleys
  - Gearing
  - Other
- The math of power transmission
- Types of gear trains
- Other power transmission topics

Linkages

- Rigid members connected with rotational freedom with respect to each other
- Good for:
  - Odd trajectories
  - Converting between linear movement and rotation
  - Reliably synchronous movement
- Downsides:
  - Potential for vibration
  - Heavy / higher inertia



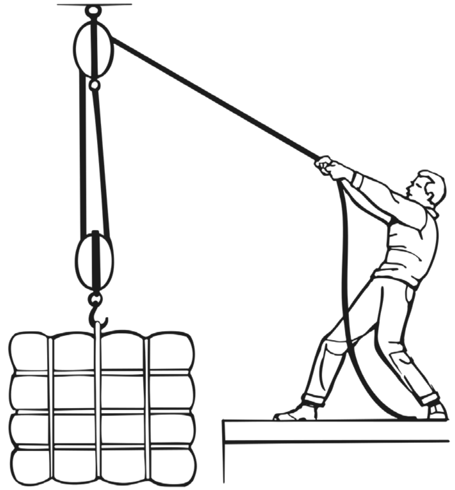


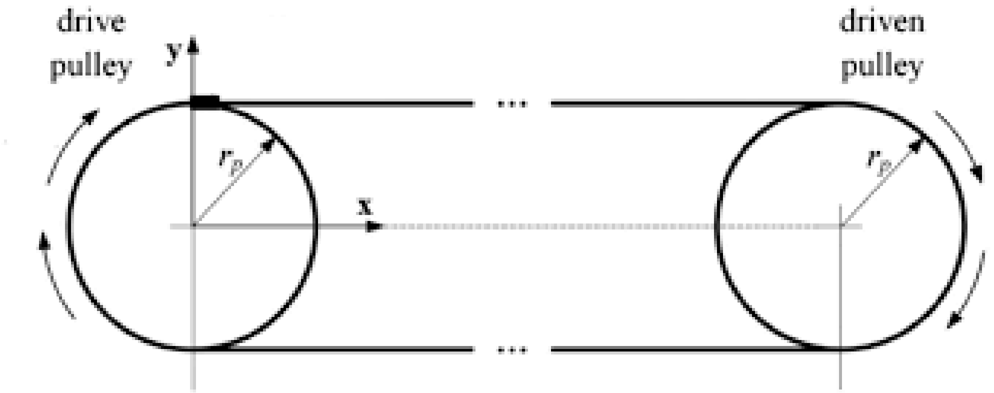
Linkages

Movie Break!

Belts & Pulleys

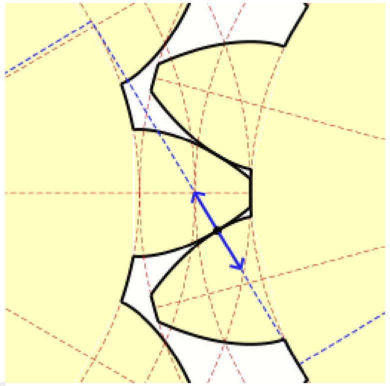
- Flexible linkages
  - Belt
  - Rope
  - Chain (kinda)
- Pulleys redirect tension
  - Mechanical advantage by doubling
- Timing belt and chain slips less
- Example
  - Direction of rotation is the same
  - “Gear Ratio” is $\frac{r_{drive}}{r_{driven}}$
  - Work in = Work out*efficiency
    - A smaller gear moves faster
    - A larger gear moves with higher torque

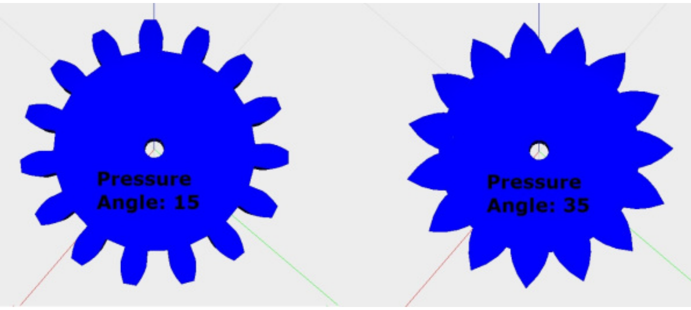


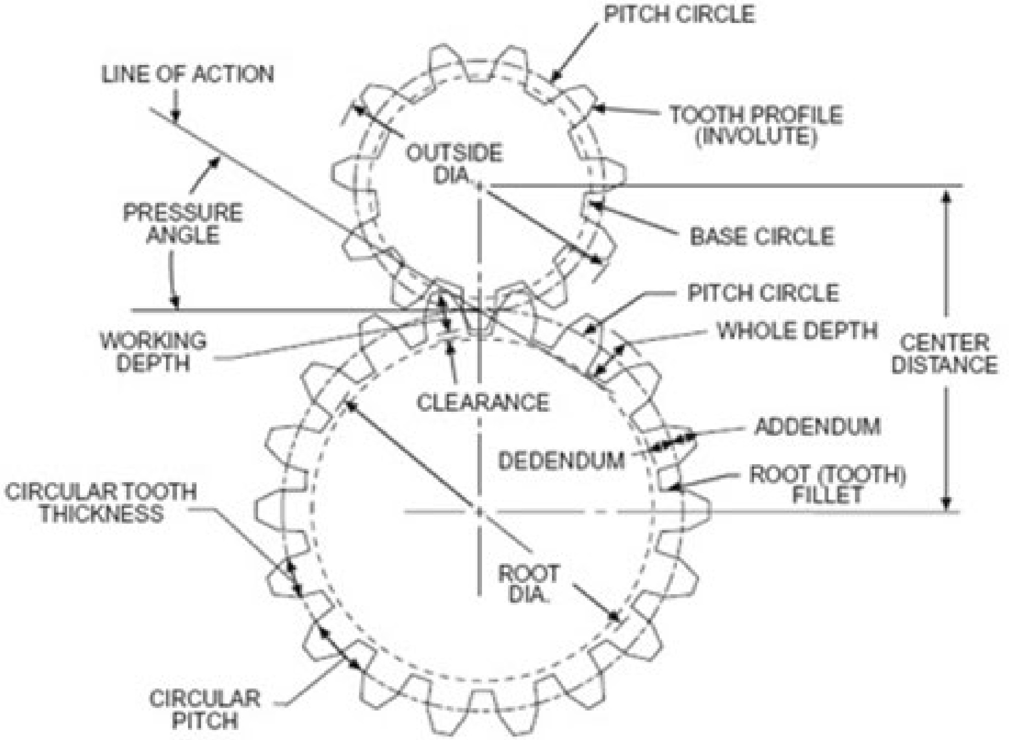


Gearing

- Interlocking teeth transfer power
  - Force exerted on each tooth
- Involute gearing
- When designing:
  - Pressure Angle
  - Module
  - Tooth count

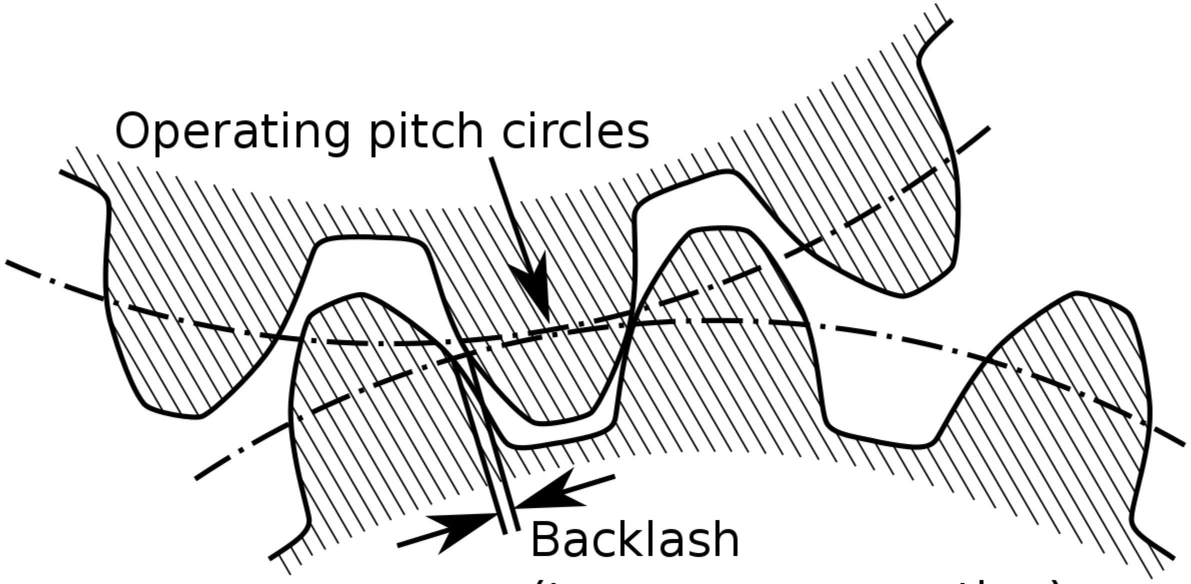






Backlash

- Due to manufacturing imperfections
- Very difficult to prevent, but can be minimized
- Robotic headache



Gear Ratio

$$gear\ ratio = \frac{r_{drive}}{r_{driven}}$$

Conveniently, radius, diameter, and tooth number always mix by the same ratio!

Multiple gear ratios multiply together. Example: I drive a 2-start worm into a 24-tooth spur, the shaft of which drives a 40-tooth spur which drives a 60-tooth spur.

$$gear\ ratio = \left(\frac{2}{24}\right) \cdot \left(\frac{40}{60}\right) = (0.083) \cdot (0.66) = 0.055$$

So my output shaft moves 0.055 rotations for every rotation of my input shaft

Gear Ratio

BUT: My output shaft has a **much greater torque** than my input shaft:

$$torque\ ratio = \frac{\prod \eta}{gear\ ratio} = \frac{0.70\ \cdot 0.95}{0.055} \approx 12!$$

So I'm getting about **12x** as much torque out of this system after the gearing reduction

Note: my rotation is 18x slower, so I'm losing a lot of power to the inefficiency!

A practical example:

- Problem: Lift a 60kg bed to a height of 2m in less than 30 seconds.

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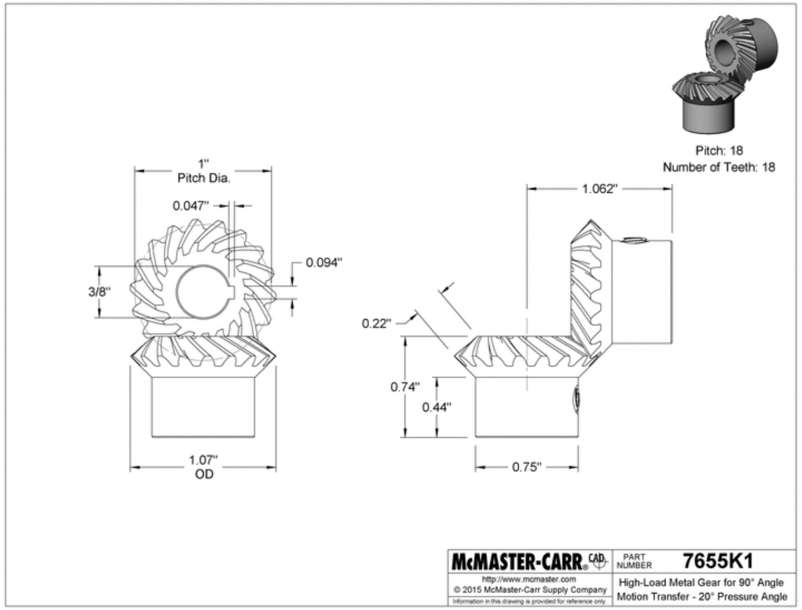
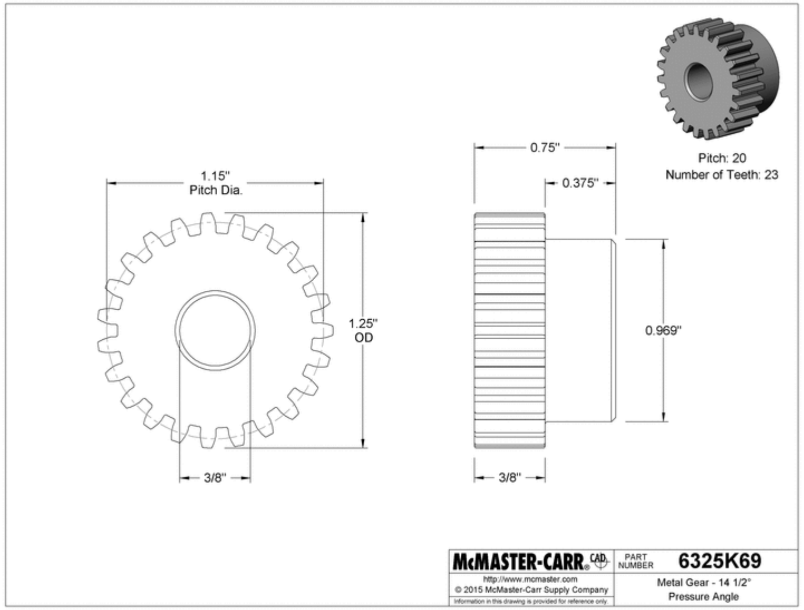
Gear Mounting

- Gear manufacturers will specify a 'pitch diameter'





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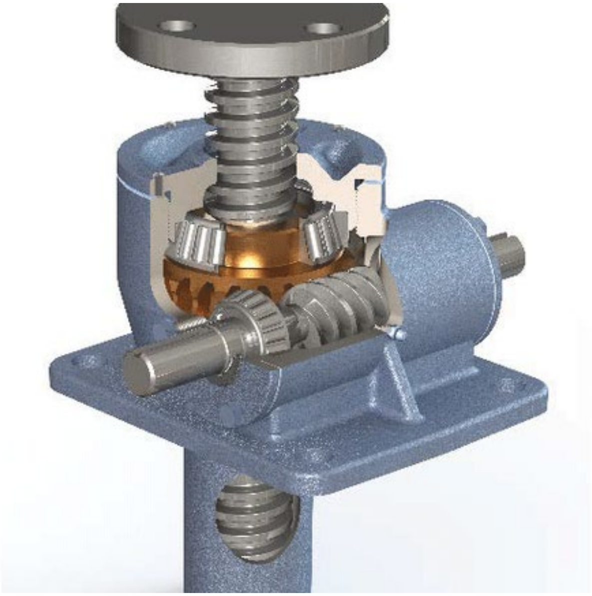
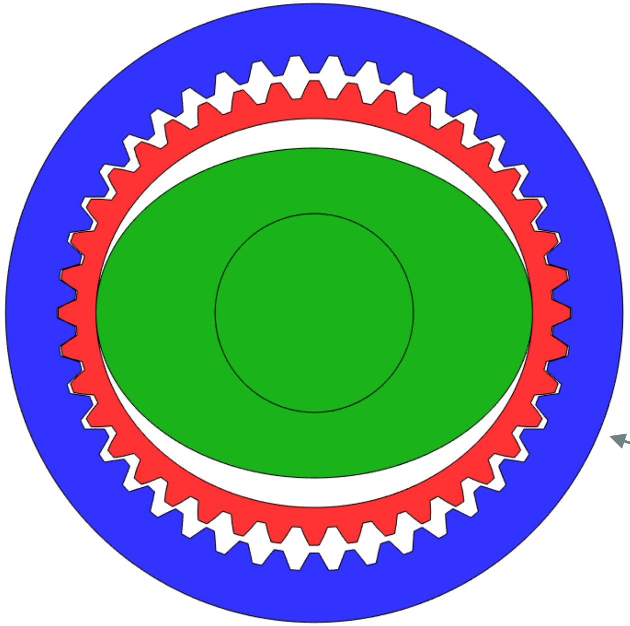
Types of Gears

- Spur gears
- Bevel gears
- Worm gears
- Differential
- Planetary
- Other

Type	Normal Ratio Range	Pitch Line Velocity (m/s)	Efficiency Range
Spur	1:1 to 6:1	25	98-99%
Helical	1:1 to 10:1	50	98-99%
Double Helical	1:1 to 15:1	150	98-99%
Bevel	1:1 to 4:1	20	98-99%
Worm	5:1 to 75:1	30	20-98%
Crossed Helical	1:1 to 6:1	30	70-98%





Harmonic Drive = zero backlash!

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Spur Gears

- Simple
- Cheap
- Easy to manufacture
- High efficiency
- Bulky
- Parallel axes
- Large range of gear ratios

- Helical Gears*
  - Like spurs, but higher torque
  - Smoother and quieter
  - More expensive

Bevel Gears

- Coplanar shafts at angles
- High efficiency
- Common
- Large range of gear ratios
- Straight- and spiral-toothed gears
- Crown Gears

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Worm Gears

- Very high gear ratios
  - Worm gear has ‘teeth’
- Very compact
  - Not coplanar rotation
- Medium efficiency
- Medium cost
- Crossed-helical gears:

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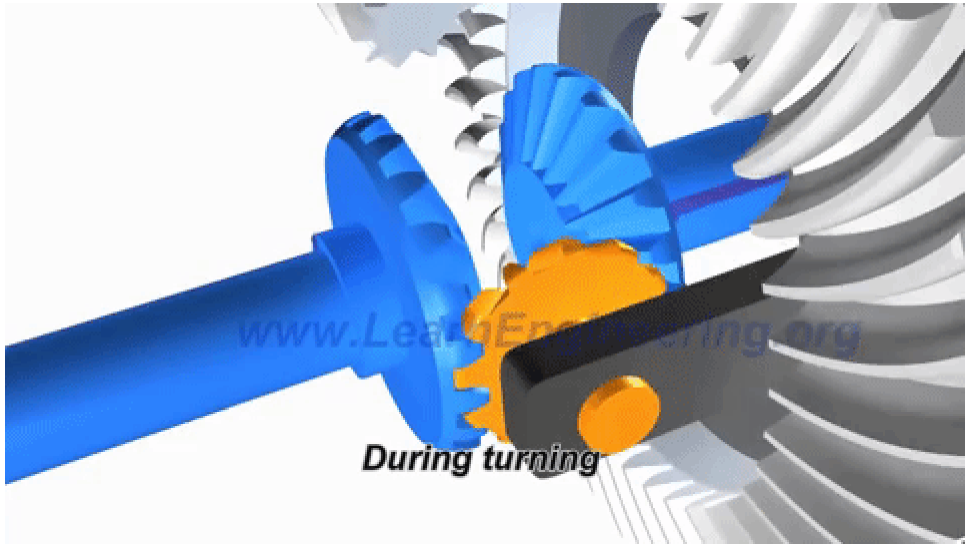
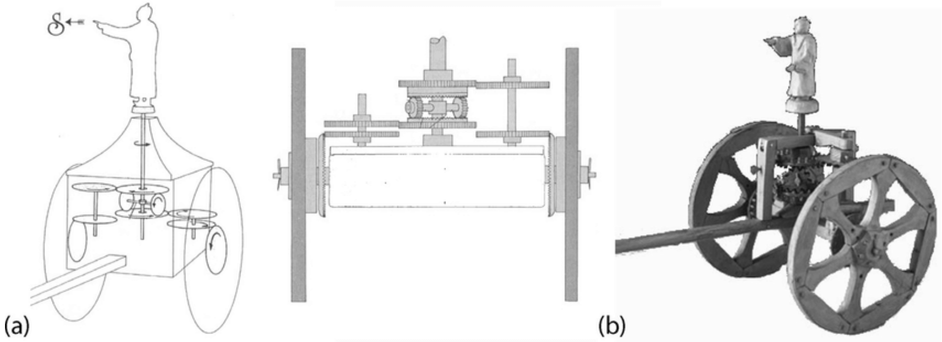
Differential

- 5+ gearing system
- Diverts power between two output shafts
- Drive wheels in vehicles which turn



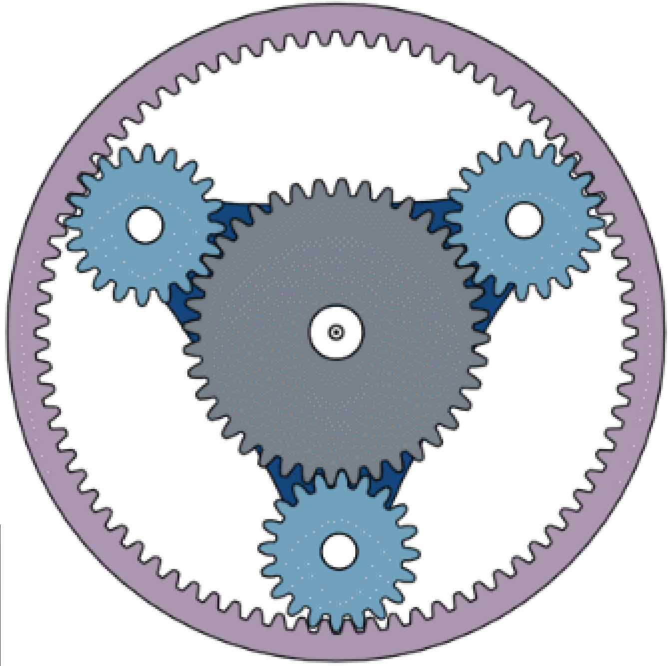


Differential

Movie Break!

Planetary Gears

- aka "epicyclic gears"
- Very compact!
- Co-axial
- Can be chained easily
- Medium and high gear ratios



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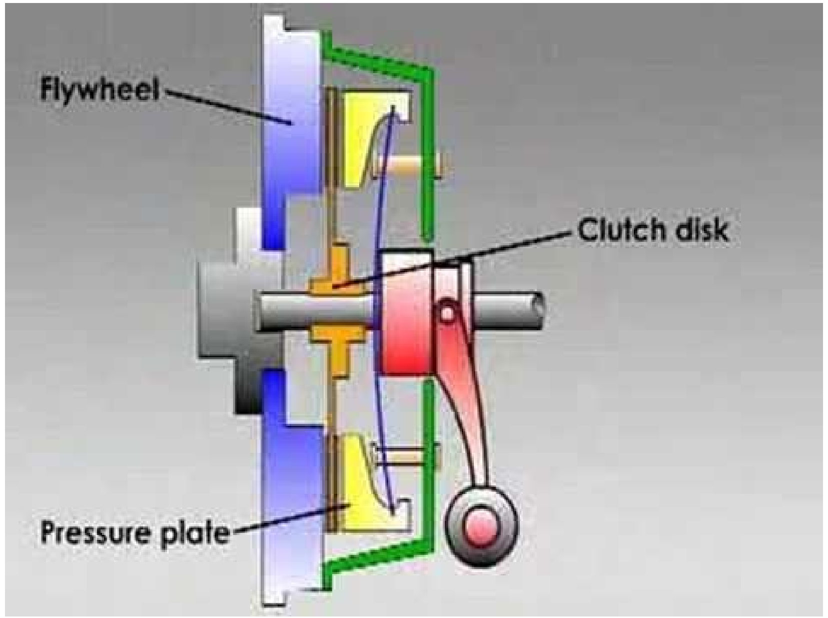
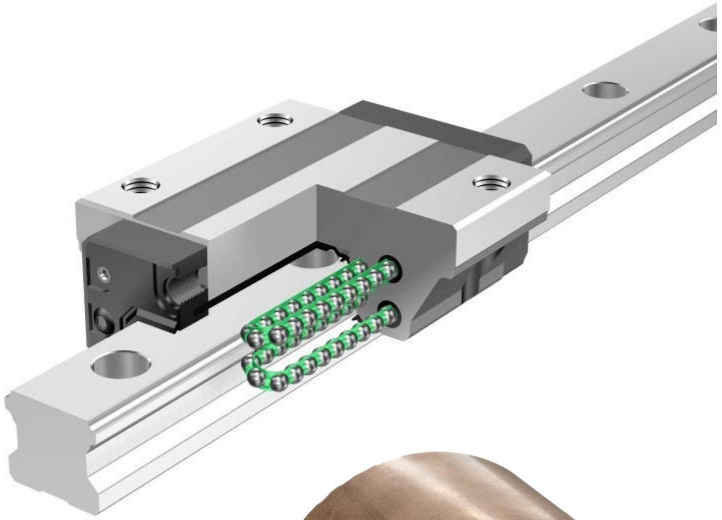
Power Transmission: Other

- Clutches
- Rack & Pinion
- Bearings
- Threaded Rods



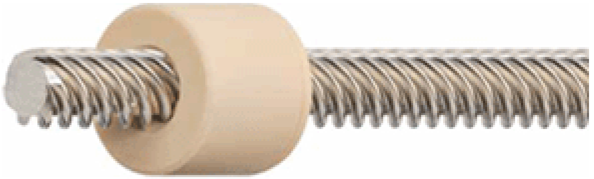
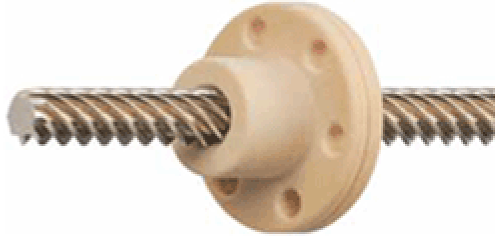
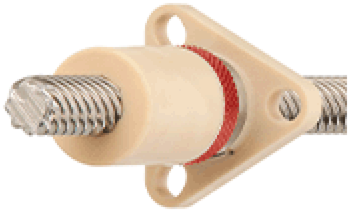
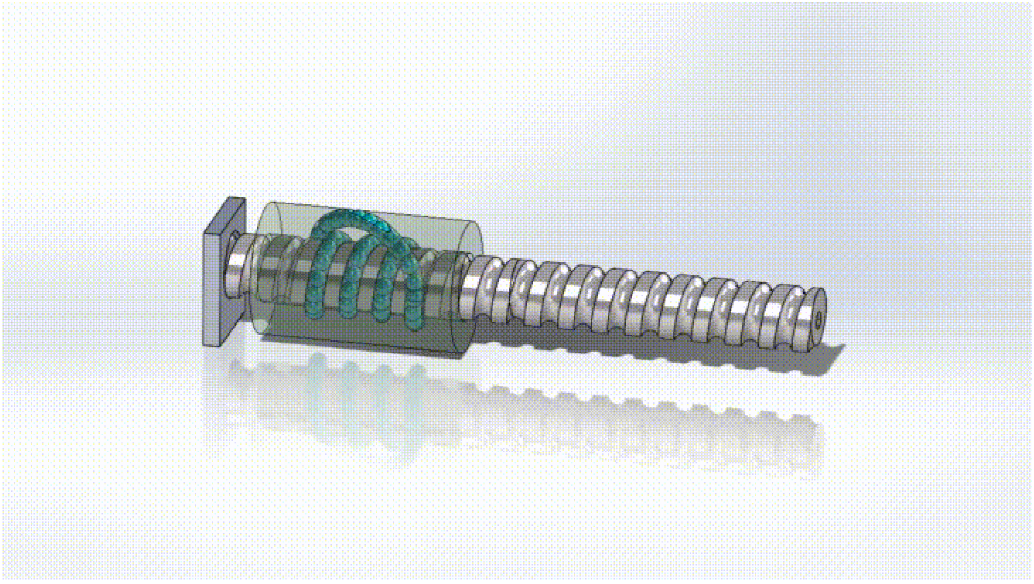
Bearings

- For smooth relative motion
- Journal/Plain bearings
  - Cheap, compact
  - Low max RPMs
  - Can be radial, axial, or both
  - Require lubricant
- Ball bearings
  - Cheap
  - High max RPMs
  - Typically radial, but can be axial/both
- Needle & Roller bearings
  - Expensive, can be very compact
  - High max RPMs
  - Radial, axial, or both
- Air bearings
  - Expensive
  - Very high max RPMs
- Linear bearings



Threaded Rods

- Conversion from rotational to linear
- Trapezoidal threads for moving applications
- Multi-start threads
- Ball screws
  - Minimize backlash!

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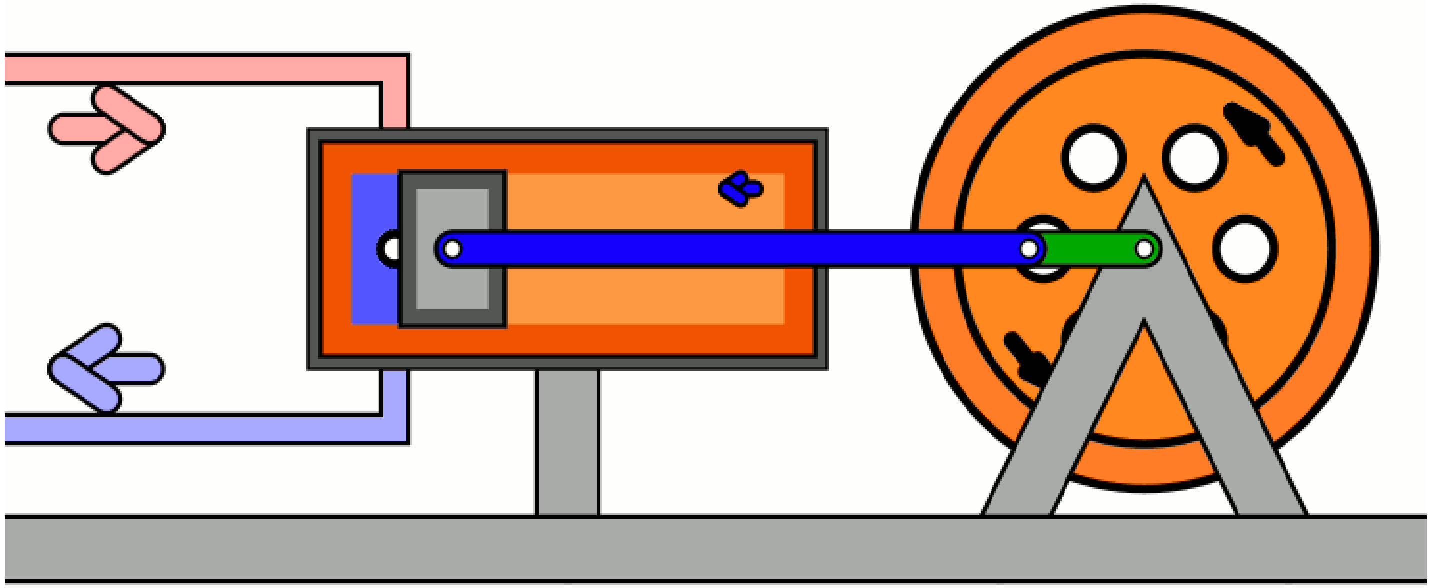
Today's Agenda

- ~~Movie Break!~~
- ~~Intro to Motion~~
- ~~Power Transmission~~
- Linear Actuation
- Rotary Actuation

Linear Actuation

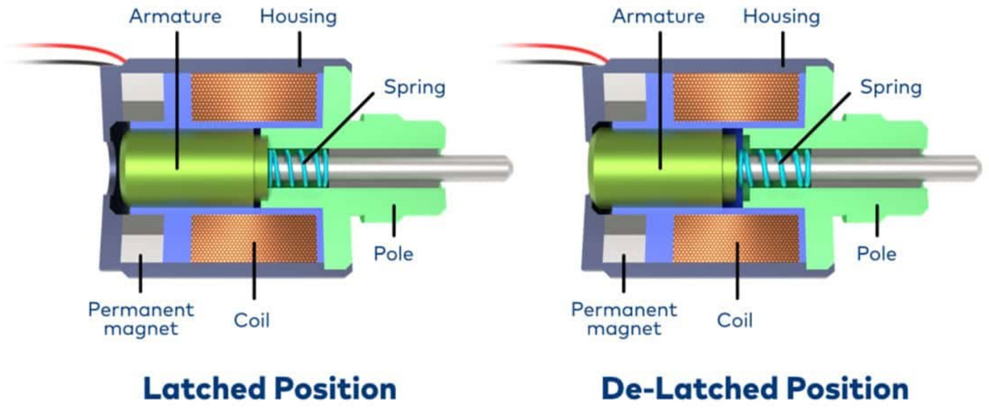
Linear Actuation

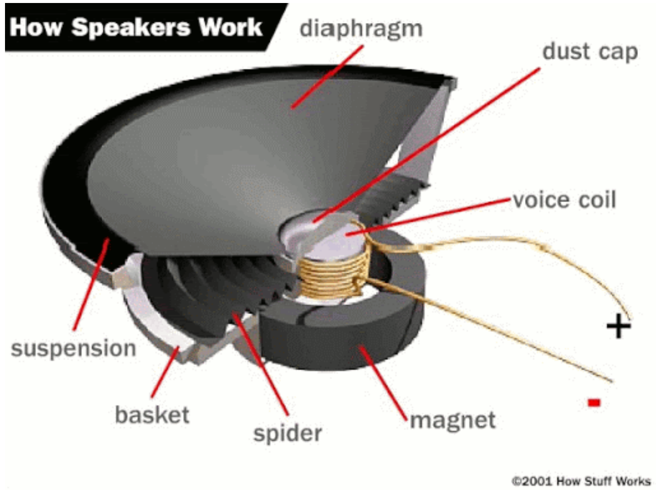
- Solenoids
- Pneumatics/Hydraulics
- Electrical linear actuators
- Others



Solenoids

- Electric coil with magnet
  - Linear movement between two points
  - Can be spring-return or latching
  - High power draw when active
  - Huge inductive load
    - use a flyback diode!
- Speakers
  - Linear movement in range
  - Displace fluid in waves to create sound
- Microphones
  - Just reverse-speakers





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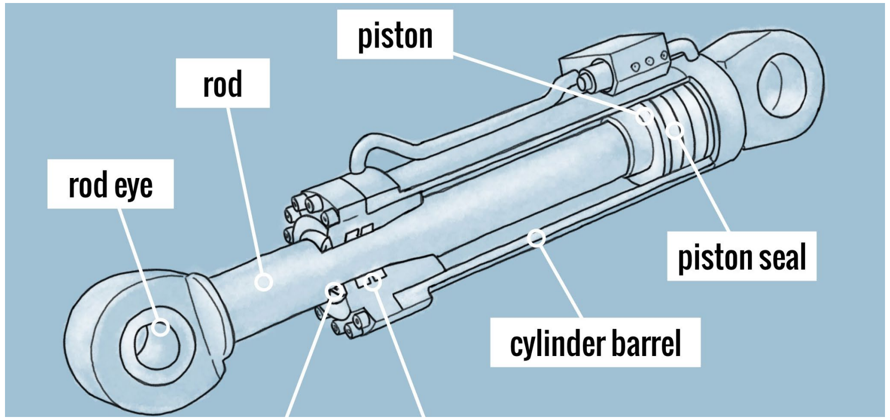
Pneumatics/Hydraulics

- Pneumatic cylinders
  - Simple, fast operation between two points
  - Spring-return or dual-acting
  - Uses compressed air
  - Solenoid valves allow easy electronic integration
  - Please use a speed controller
- Hydraulics
  - Slower, extremely high-force operation in linear range
  - Tend to be expensive
  - Requires liquid (typically hydraulic fluid)
  - High pressures, so system must be robust



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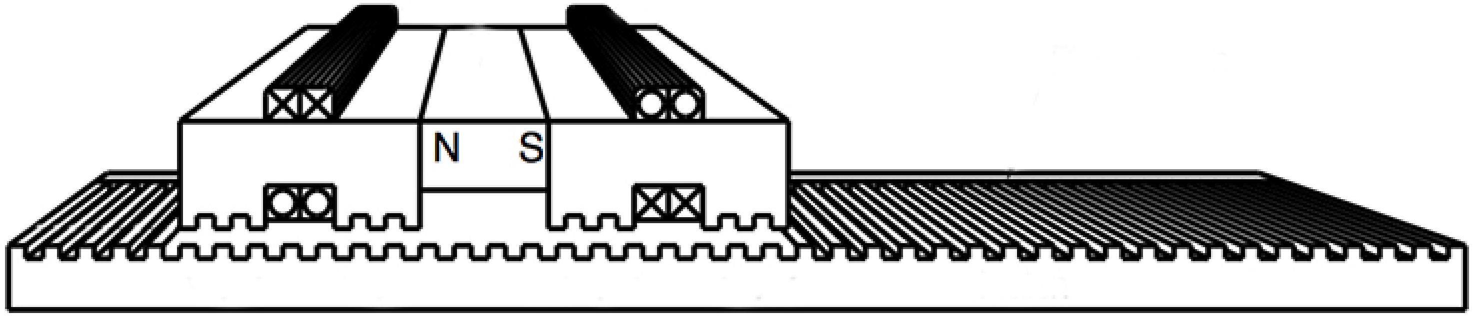
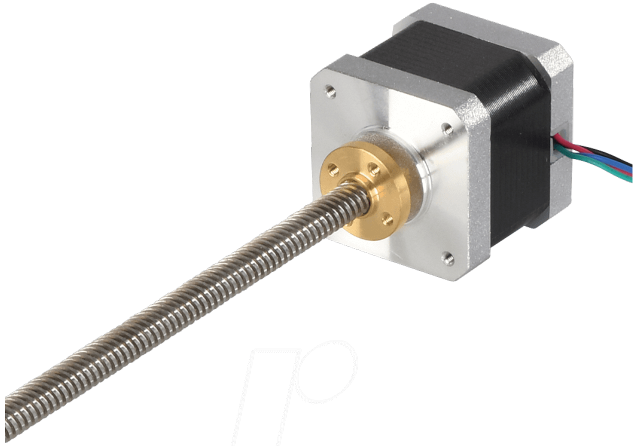
Electrical Linear Actuators

- Linear stepper
  - Expensive
  - Easy to implement
- Rotary-to-linear
  - NCLAs
  - Ball screws
  - Threaded rods





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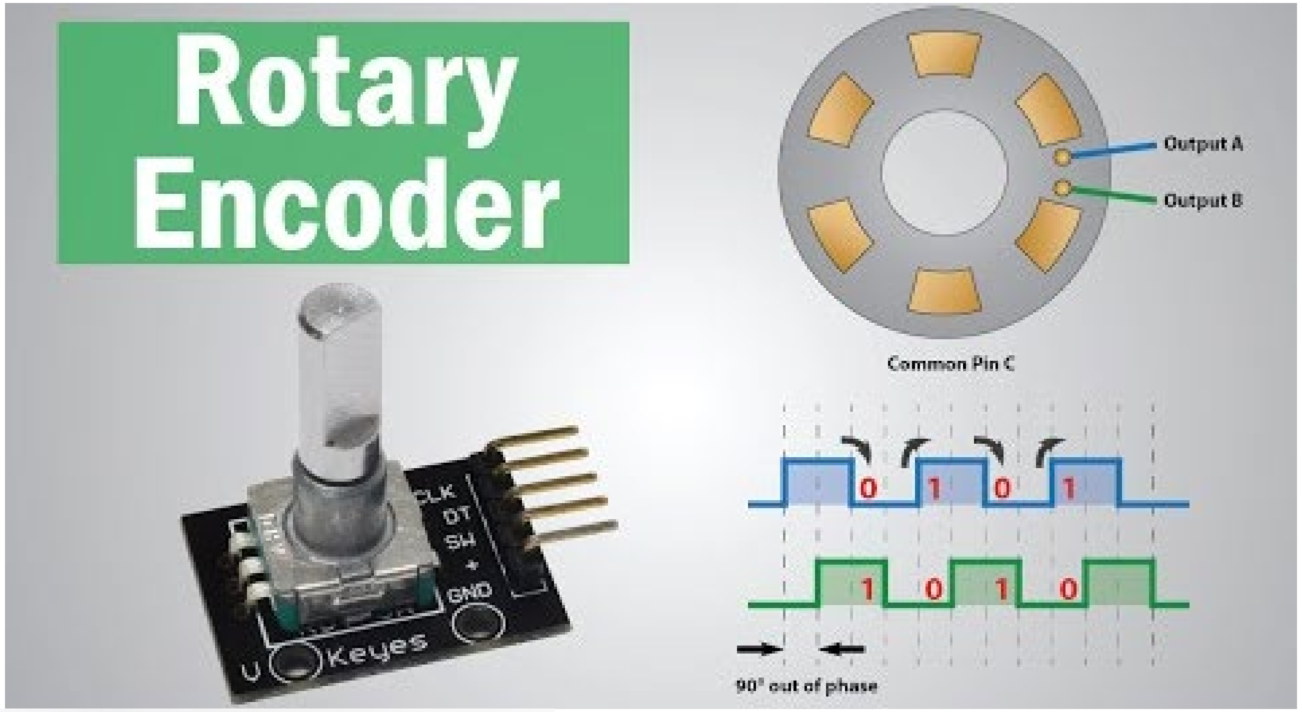
Rotary Actuation

Rotary Actuation

- Sensors
  - Rotational Encoders
  - End switches
  - Hall Effect Sensors
- Actuators
  - DC Motors
  - (Micro)servos
  - Steppers



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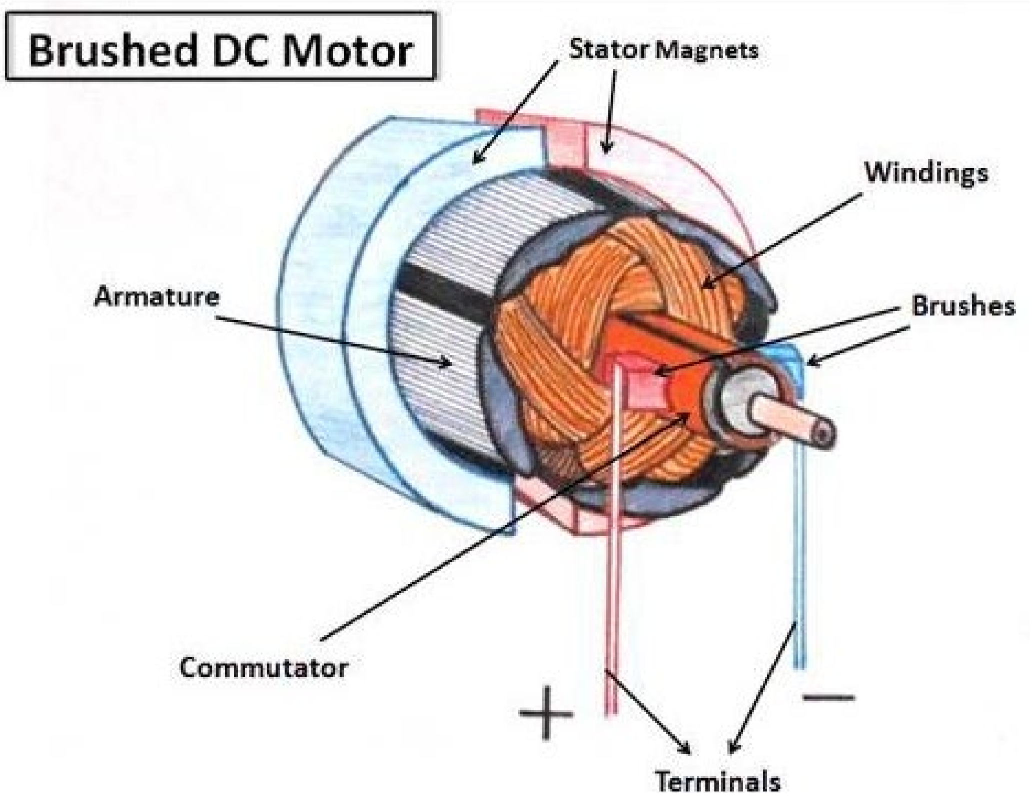
DC Motors

- Brushed
  - Extremely cheap
  - Require H-bridge to control speed, direction
  - Terrible for open-loop control
  - Require sensors for closed-loop control
  - Low precision



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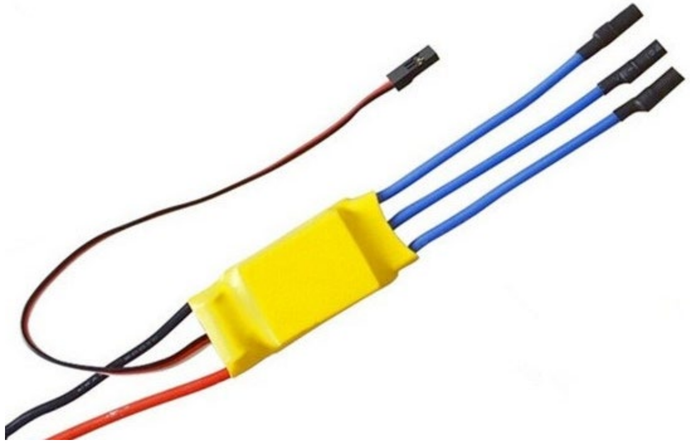
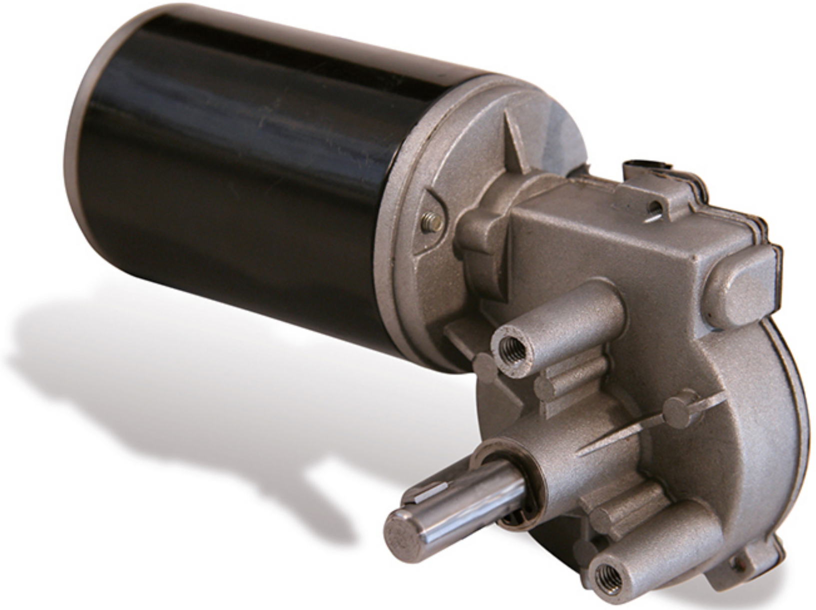
DC Motors

- Brushless
  - High RPM
  - Requires electronic speed controller (ESC)
  - Drone applications: light and high RPM
  - Also requires sensors for positioning
    - Same problems with control
  - Low precision



Gear Motors

- Brushed motors with gearing!
  - High torque/low RPM
  - Compact
  - Cheap
  - Still not great for control
    - Slower RPM makes tracking position easier



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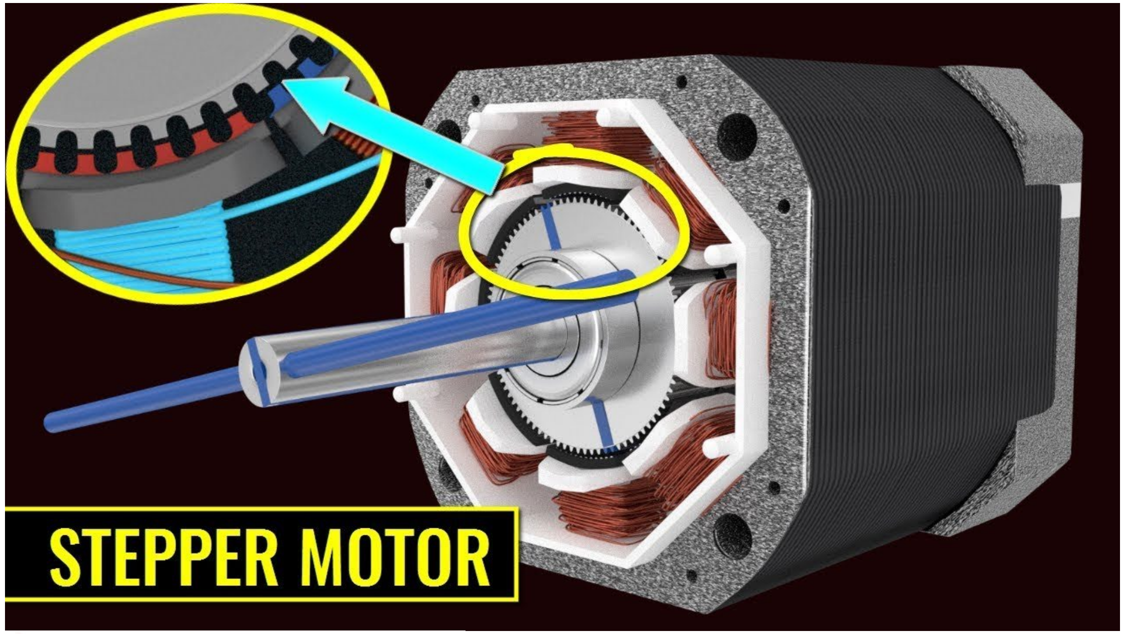
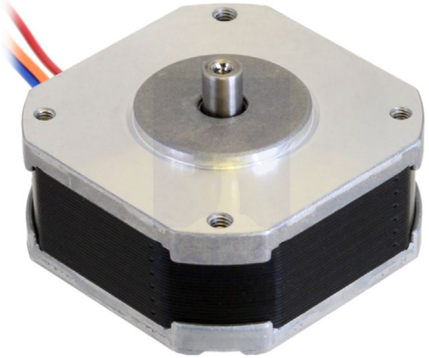
Servomotors

- Motors with feedback!
  - More complicated to use
  - Internal closed-loop control
- Micro-servos
  - Very light
  - High torque
  - Limited range of motion

Stepper Motors

- Uses alternating coils to advance rotation in small increments
  - Usually specify 1.8 degrees/step or 0.9 degrees/step
- Low RPM (max ~1200)
- High torque
- Steps allow very precise movement
- Coils can 'brake', preventing movement
- Pretty cheap
- Requires stepper driver





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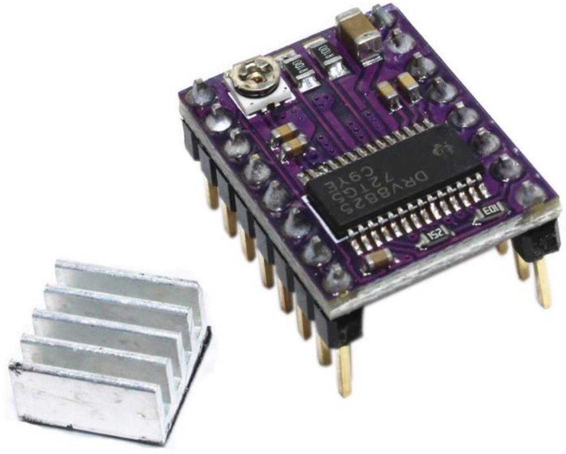
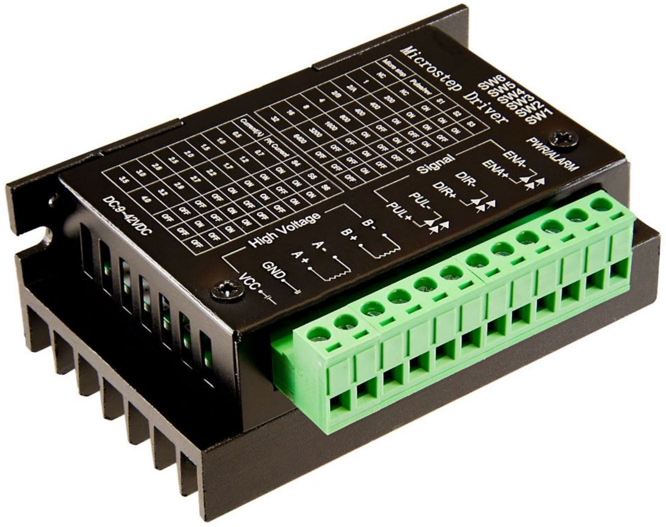
Stepper Drivers

- Drivers are current limiting
  - Prevents coil burnout
- Torque is voltage based
  - Steppers can be driven above listed voltage if good drivers are used
- Microstepping can increase precision to 16x or 32x step increment!
  - 0.9 degrees / 32 = 0.028 degrees
- Can be used with open-loop easily
- Need sensors for closed-loop control





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Engineering is about persistence.

Stuff will break. If you can build it, you can fix it.

Questions? Office Hours!

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