ELECTROMECHANICS, ACTUATORS

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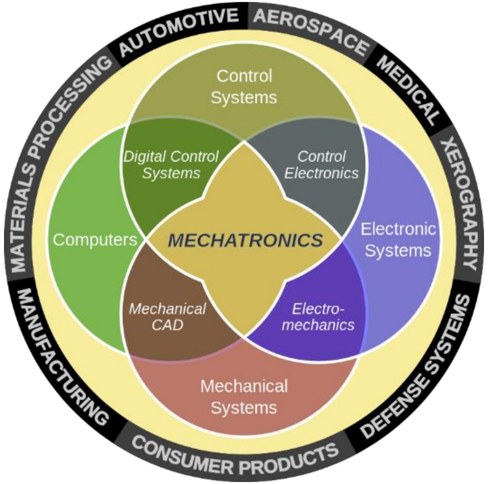
Common Topics in Mechatronics Course

- Electronic Circuits & Components
- Semiconductor Electronics
- System Response
- Analog Signal Processing using OpAmps
- Digital Signals & Logic
- Microcontroller Programming & Interfacing
- Data Acquisition
- Sensors
- **Actuators (motors/gears/encoders)**
- Component control methods (Bang-bang, PID, etc.)
- System control architectures (state machines)



What will you learn today?

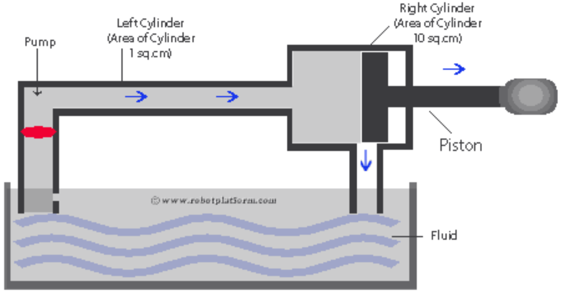
- What is an actuator?
  - How to spec. an actuator?
- Actuator components
  - Motors
  - Gear trains
  - Encoders
- Common actuator/motor types
- Including actuators in a circuit model

What is an actuator

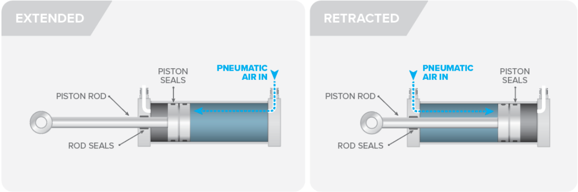
- **Actuator:** Mechanical or electro-mechanical devices that allow ***controlled*** movements or positioning often in the presence of loads or disturbances not know *a priori*.

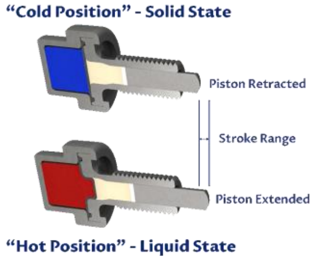
Types of actuators – Based on the source of motion

- Hydraulic actuator
  - A liquid creates motion of a mechanical element
- Pneumatic actuator
  - A gas creates motion of a mechanical element
- Electromechanical actuator
  - Electrical energy is transformed into motion of a mechanical element
- Thermal Actuator
  - Thermal energy creates motion of a mechanical element



Hydraulic Actuator



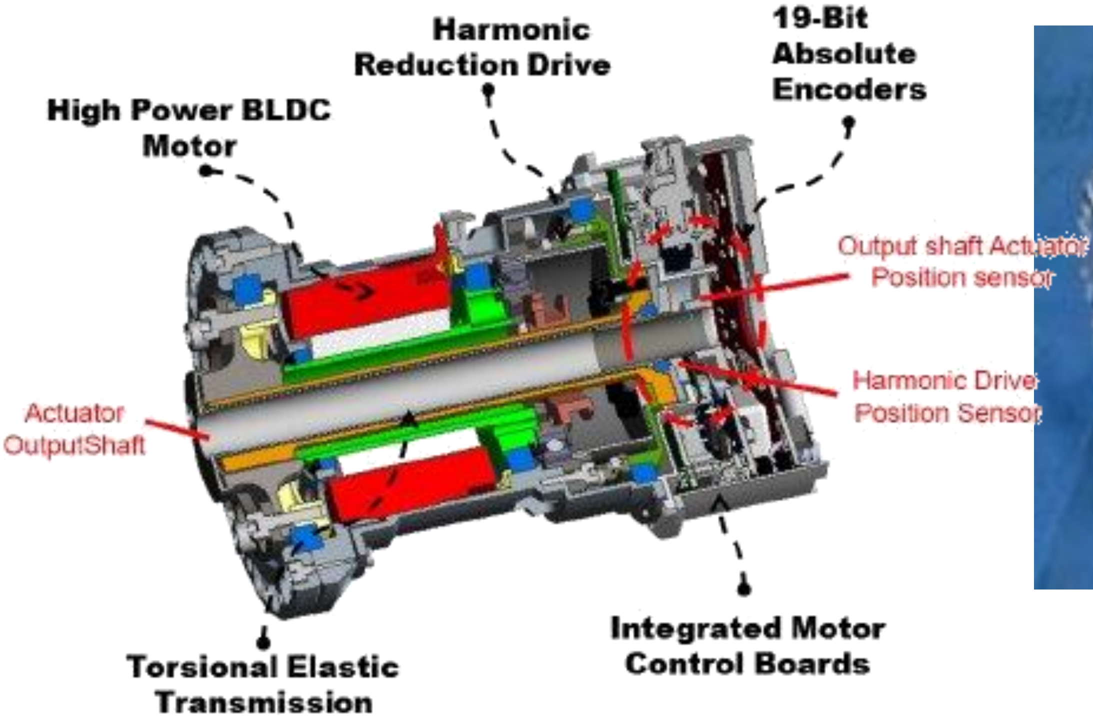


Types of actuators – Based on motion

- Linear Actuators
  - Create linear motion -- translation

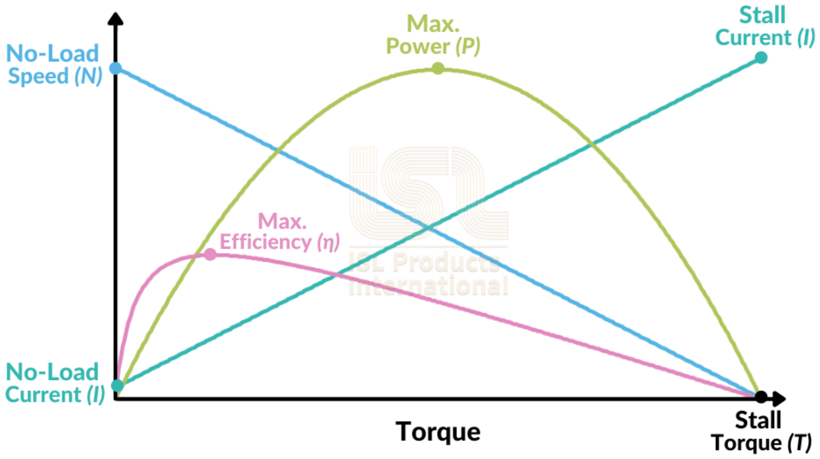
- Rotary Actuators
  - Create rotational motion
  - Most robot arms and bases use this

Common Components of a Rotary Electromechanical Actuator

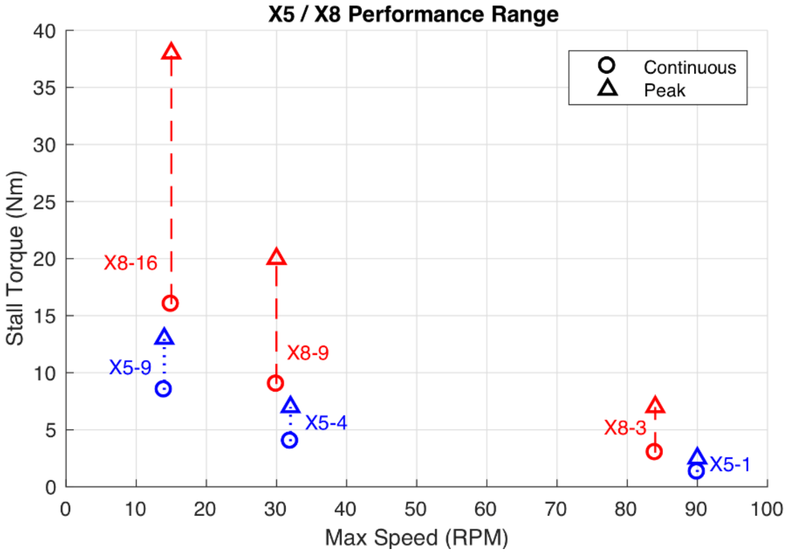


Specifications of an Actuator

- https://docs.hebi.us/hardware.html#x-series-actuators

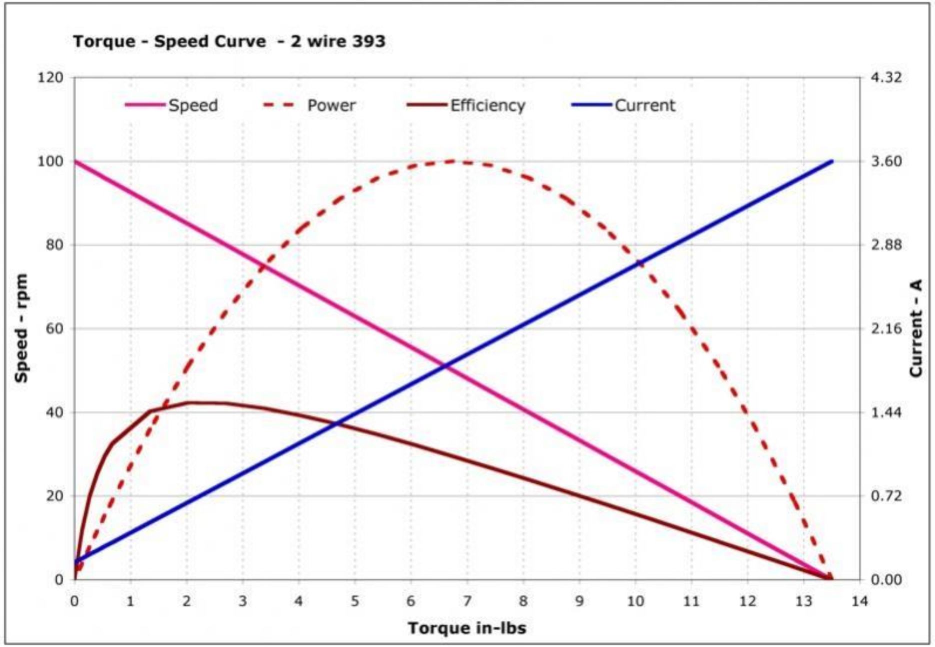


Torque/speed curve



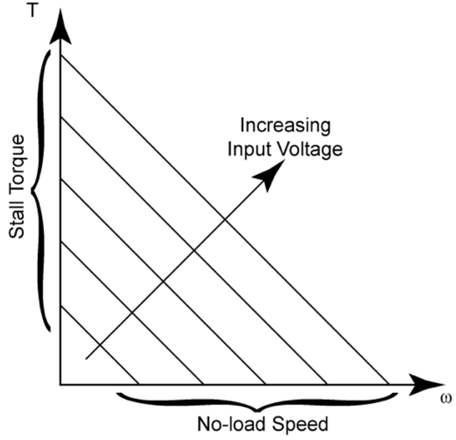
Torque-Speed Curve in an Actuator

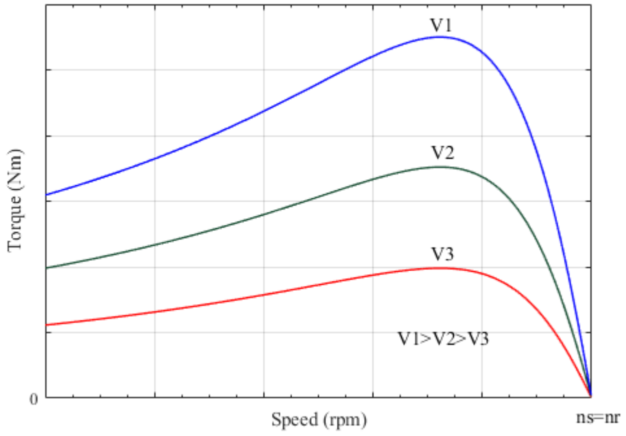
- $\tau = -k_1\omega + k_2$
- $\omega = -k_1'\tau + k_2'$
- No load ($\tau_n = 0$):
  - Velocity is maximum: v_n
  - Current is minimum: i_n
- Stall ($v_s = 0$):
  - So much load that the motor stops (speed=0)
  - Stall torque: τ_s
- (Output) Power:
  - $P = \frac{dW}{dt}$
  - $P = \tau \cdot \omega$ [watt or Nm/s]
- Efficiency:
  - Relationship $\eta = \frac{InputPower}{OutputPower}$
  - At the max of efficiency we get the “rated” values:
    - Rated speed
    - Rated torque
    - Rated current
    - Rated power



Torque-Speed Curve and Dependency to Voltage

- As we increase voltage:
  - Stall torque increases
  - No load speed increases

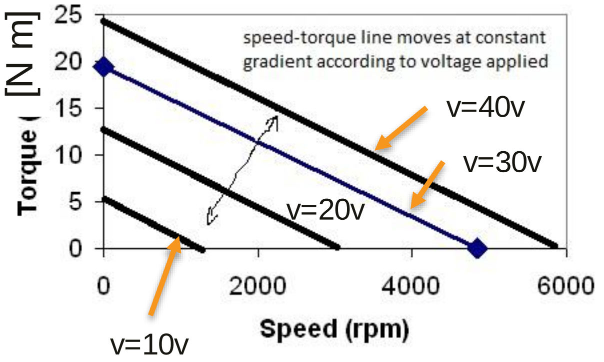




https://pollev.com/robertomartinmartin739

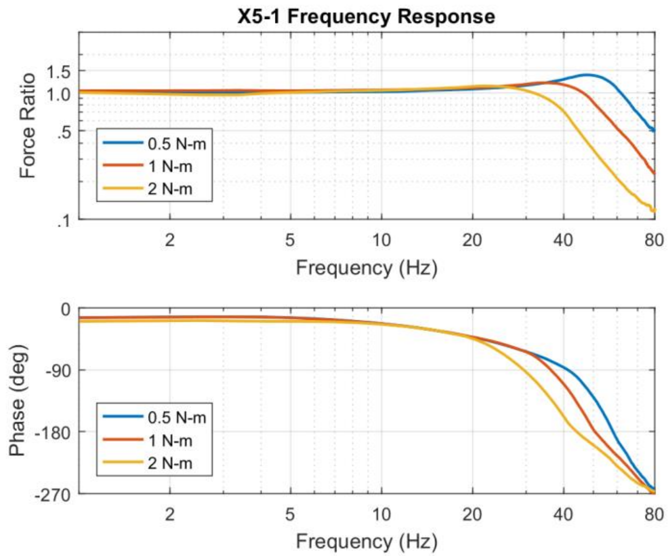
Exercise

- Assuming a motor with the following curves for torque-speed, we want to move a robot hand of mass 1 kg in a robot arm of length 0.5m (we can ignore the arm mass) at a maximum speed of 2000 rpm
- What would be (approx.) the maximum voltage we would need to apply?



More Specifications of an Actuator

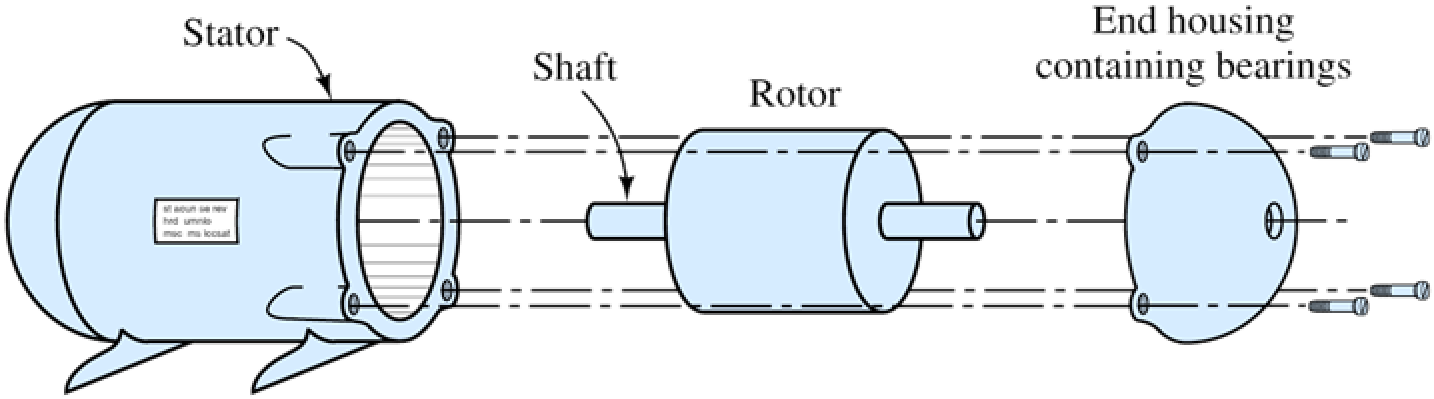
- https://docs.hebi.us/hardware.html#x-series-actuators



- Max/Continuous Torque
- Torque/Speed Curves
- Current/Power Draw
- Joint Velocity/Position Limits
- Frequency Response (Bode Plots)
- Mechanical Loading Limits
- Electrical/Motor Parameters
- Mechanical Load Bearing Limits
- Kinematic Reference Frame(s)
- Wiring/Bus type
- Power requirements
- etc.

Motors: Basic construction

- **Stator**: stationary part
- **Rotor**: rotating part connected to shaft that couples the machine to mechanical load



Common motor types in robotics

- Brushed DC motors
- Servo motors
- Stepper motors
- Brushless DC motors

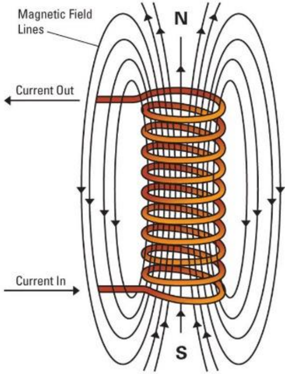
- This far from a complete list of all motors

Prior: Electromagnetism

- Maxwell Equations

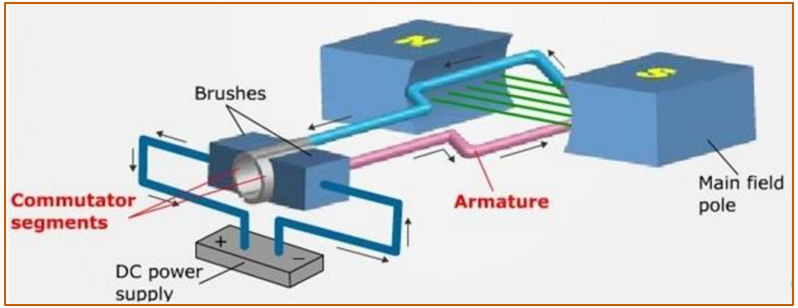
Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\, dV$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot d\boldsymbol{\ell} = -\frac{d}{dt}\iint_\Sigma \mathbf{B}\cdot d\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot d\boldsymbol{\ell} = \mu_0\left(\iint_\Sigma \mathbf{J}\cdot d\mathbf{S} + \varepsilon_0\frac{d}{dt}\iint_\Sigma \mathbf{E}\cdot d\mathbf{S}\right)$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

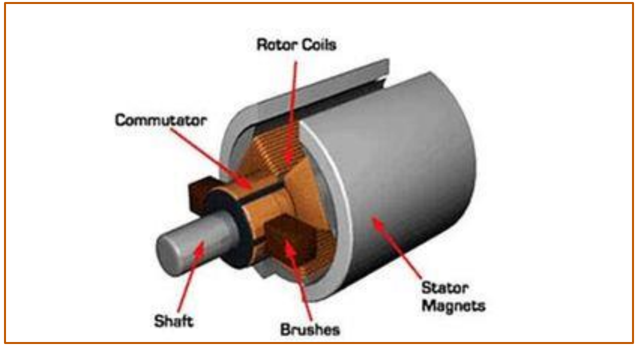
- Important for us:
  - A current will create a magnetic field
  - We will use this to create motion using current



Brushed DC Motor

- How it works:
  - Motor contains many copper windings surrounded by magnets
  - DC Voltage applied at the input
  - This induces a current in the armature
  - Relationship between electrical current and magnetic fields induces a force
  - Force causes the motor to rotate
  - When the shaft flips around, the brushes reverse the electrical polarity, preventing the motor from bouncing back
- Simplest, most common type of motor





Source: https://www.electronicshub.org/dc-motor/
https://www.solomotorcontrollers.com/

Brushed DC Motor

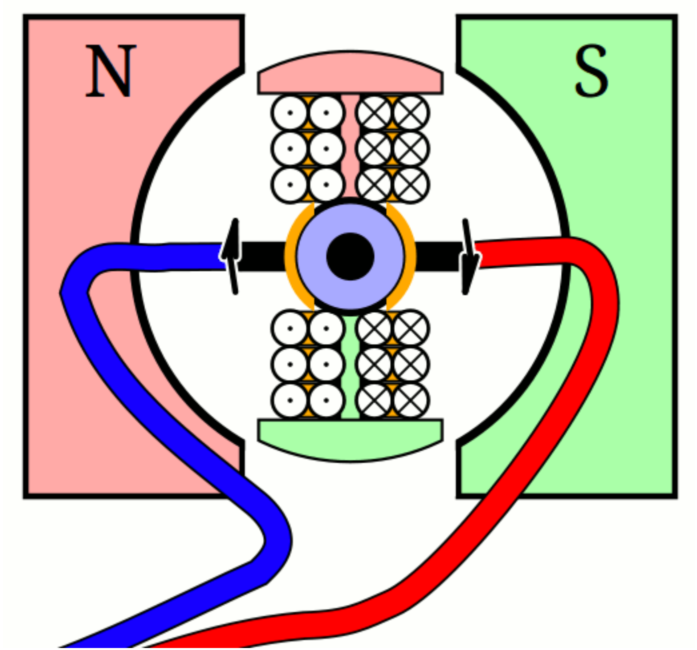
- How to identify a brushed DC motor

Only two wires, usually red and black

If you can see the brushes, they often spark on large accelerations of the motor

- Pros:
  - Cheap
  - Easy to control and install
- Cons:
  - Brushes wear out over time
  - Electrically inefficient

Brushed DC Motor in Action



Why do I keep seeing them called servo motors?

- Servos are not a different type of motor

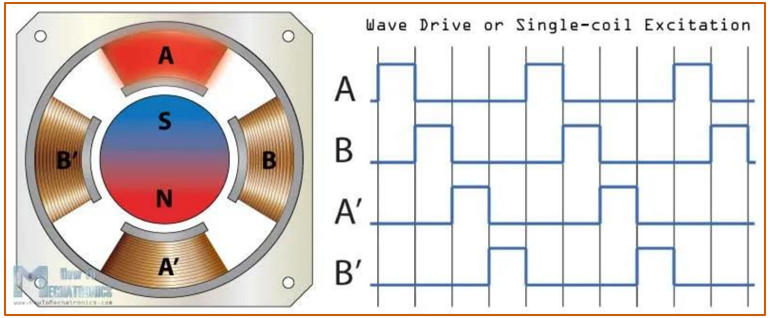
- Servos are motors with feedback control circuits built in:
  - Built in encoder
  - Usually position controlled, so you set the motor to a specific angle
  - Usually high torque, low speed, but that isn't a rule

- Most servo motors are simply brushed DC motors

- Great for high precision tasks with limited range of motion
- Not great for high speed, constantly running tasks

Stepper Motors

- Stepper motors are a form of DC motor
- They contain a permanent magnet rotor and copper windings on the stator
- For simplest operation, each winding is activated one "step" at a time to attract the rotor
- Similar use cases to Servos



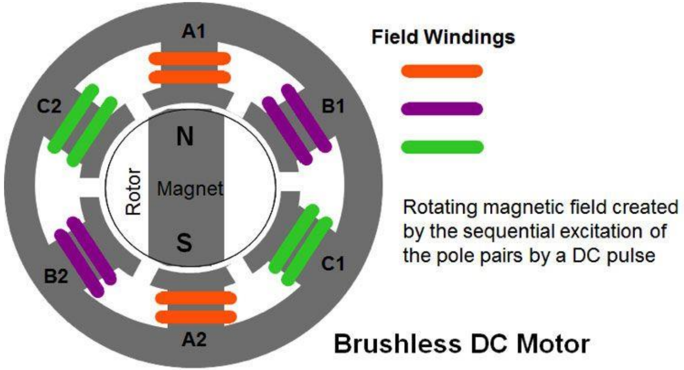
<u>Identification</u>

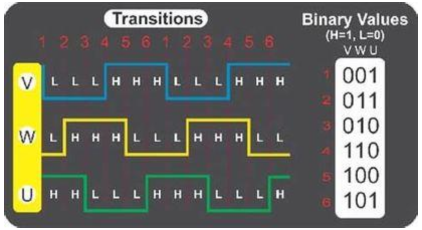
- Most easily identified by 4, 5, 6, or even 8 wires coming from the motor
- Known as unipolar, bipolar, or hybrid respectively.

https://howtomechatronics.com/how-it-works/electrical-engineering/stepper-motor/

Brushless DC (BLDC) Motors

- Brushless motors function almost identical to stepper motors
- Differences:
  - 3 Phase instead of 2 Phase
  - BLDC motors have a handful of windings, steppers have thousands
  - BLDC are designed for smooth motion
- Many brushless motors come with Hall sensors (aka a servo motor), which is acts as a 6-pulse incremental encoder





https://pmmonline.co.uk/
https://www.digikey.ca/

Brushless DC (BLDC) Motors

Identification

5 (or 6 smaller wires if there is a Hall sensor)

Three thick wires for the 3 power phases

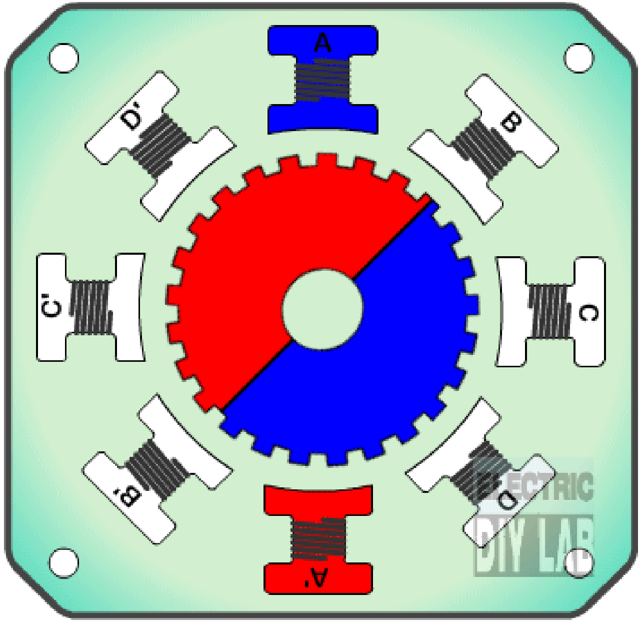
Pros

- High torque
- Very fast operating speeds
- Electrically efficient
- Long lifetime

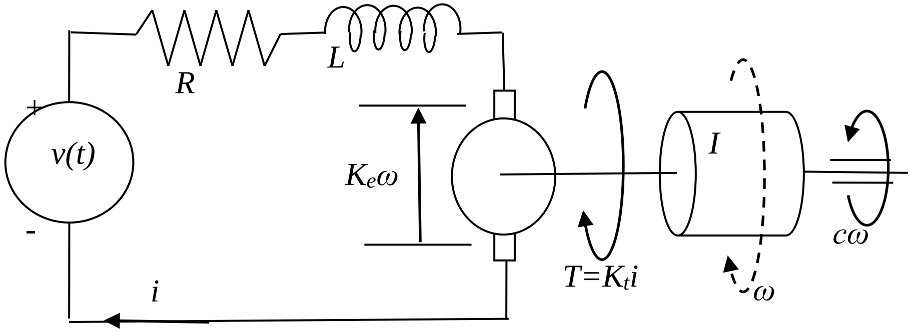
Cons

- Complicated to control
- Inaccurate at low speeds with Hall sensor
- Both motors and controllers are expensive

Stepper/Brushless DC Motors in Action



A simple circuit with a motor



Voltage drop across the resistor

Voltage drop across the motor is a function of the its angular velocity.

$$L\frac{di}{dt} = -Ri - K_e\omega + v(t)$$

First order equation for a RL circuit

Battery or other voltage source

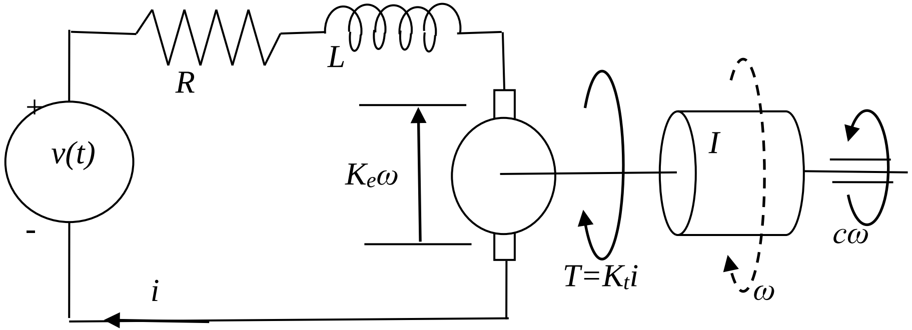
Newton's 2nd law for angular acceleration.

Friction in the bearing is a function of the angular velocity.

$$I\alpha = K_t i - c\omega$$

Simple linear model for the torque-speed curve.

A simple circuit with a motor



$$L\frac{di}{dt} = -Ri - K_e\omega + v(t)$$

$$I\alpha = K_t i - c\omega$$

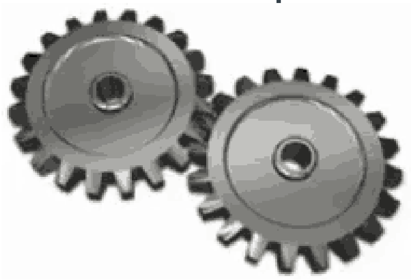
$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix} = \begin{bmatrix}-\frac{R}{L} & -\frac{K_e}{L}\\ \frac{K_t}{I} & -\frac{c}{I}\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}\frac{v(t)}{L}\\ 0\end{bmatrix}$$

- *Example: Armature controlled DC 'Direct Drive' Motor*
  - *Simplest model is 2 coupled 1st order differential equations*
  - *The motor is included in the circuit using a constant that maps current to torque.*
  - *The motor torque is included in the dynamic equation (Newton's 2nd law) as constant that maps current to torque.*

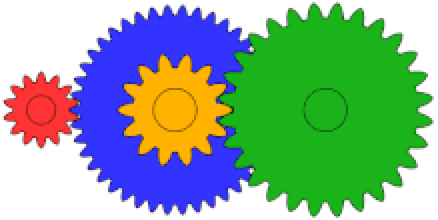
If the states are *i* and *w*, *then the linear equations can be written in a standard state-space form for a controller.*

Gear train

- The use of gears to provide a *mechanical advantage* between the input and output device or provide some other desired characteristic in the output.



simple spur gear



compound gear train

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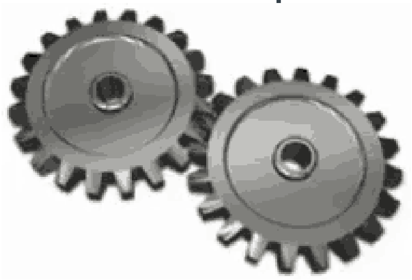

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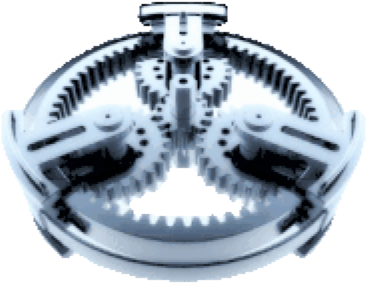

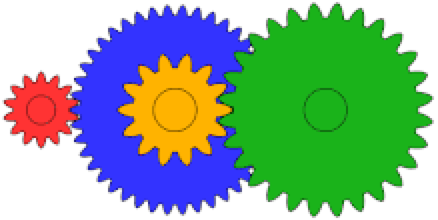

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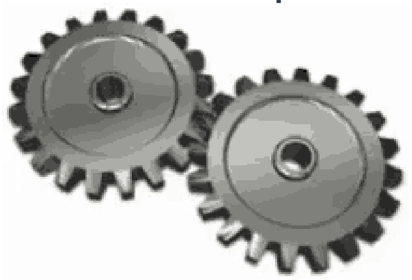

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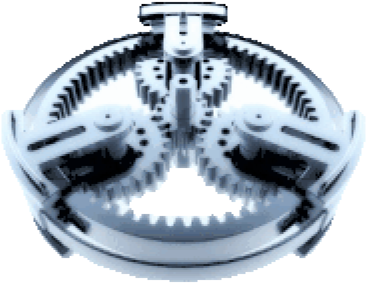
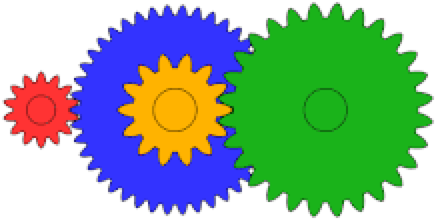


epicyclic / planetary gear



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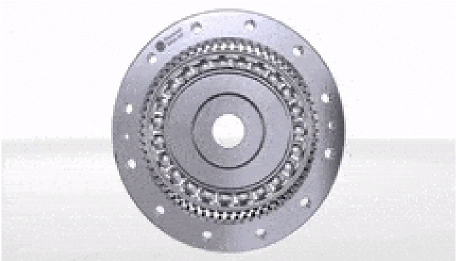

harmonic gear train

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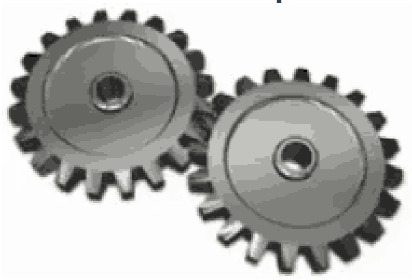
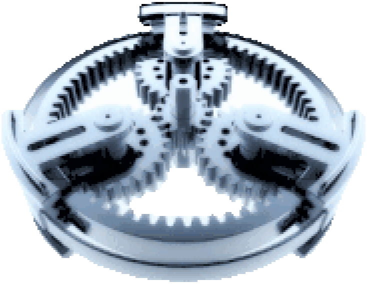


simple spur gear



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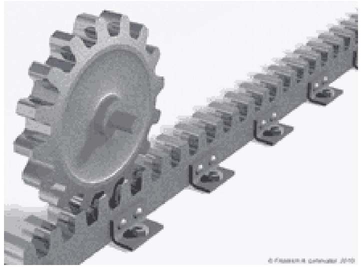
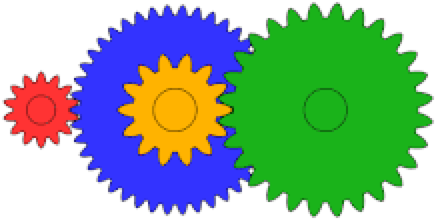


rack and pinion



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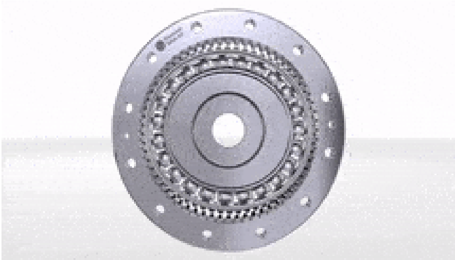

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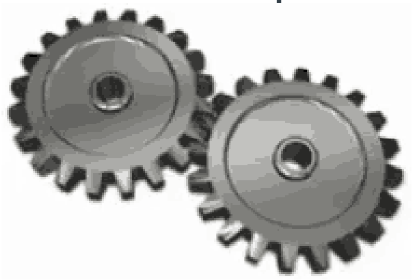

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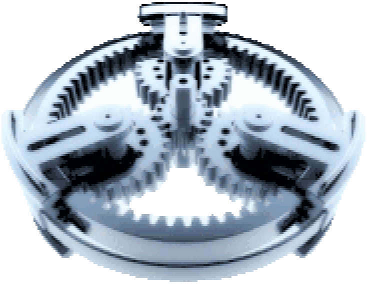

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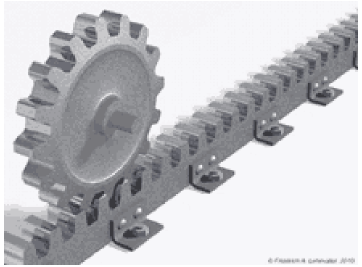

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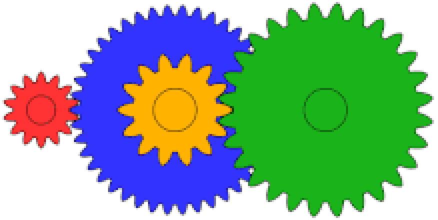

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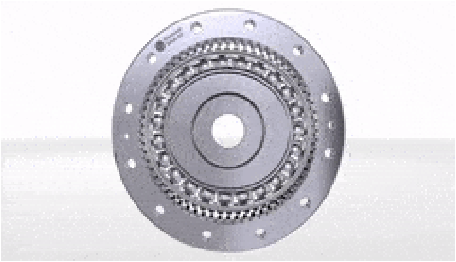
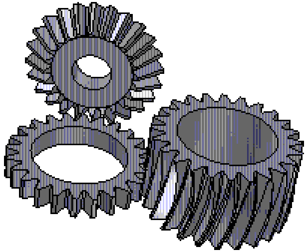


harmonic gear train



bevel (top) and helical (right)

Gear train

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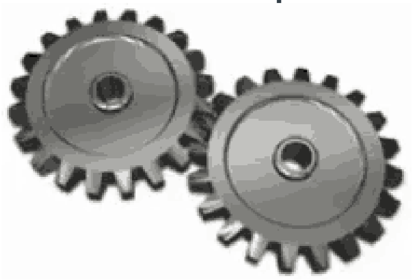
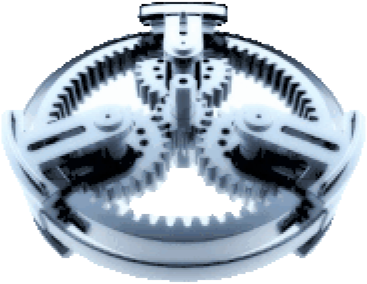
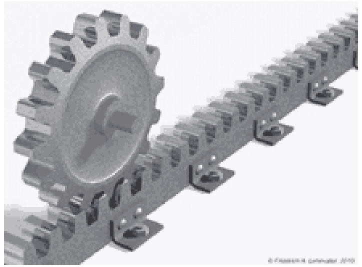


simple spur gear



epicyclic / planetary gear



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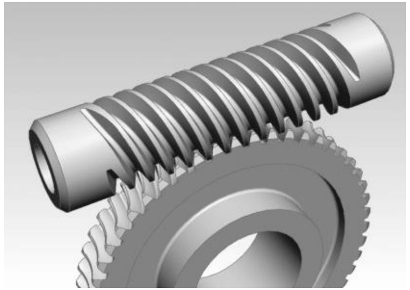
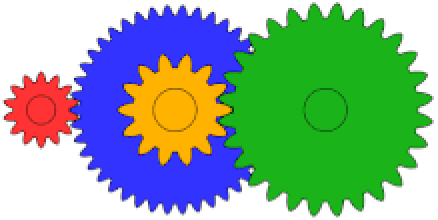
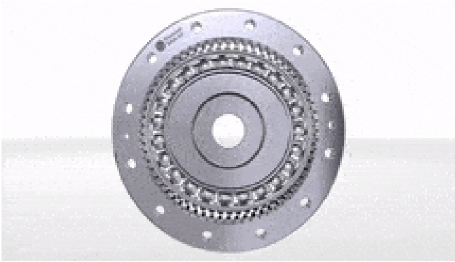


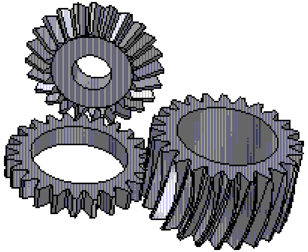
worm gear (this one is right-handed)



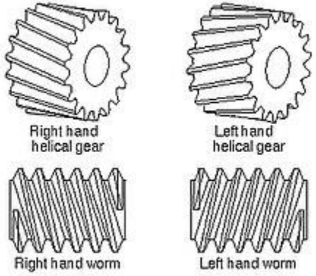
compound gear train



harmonic gear train



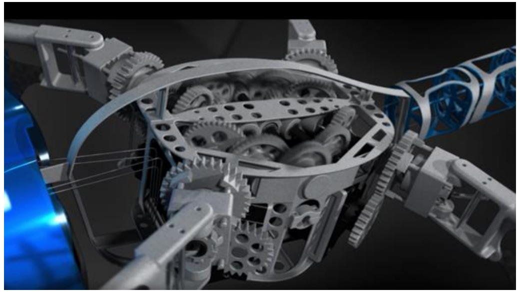
bevel (top) and helical (right)



gear handedness

Gear-train example

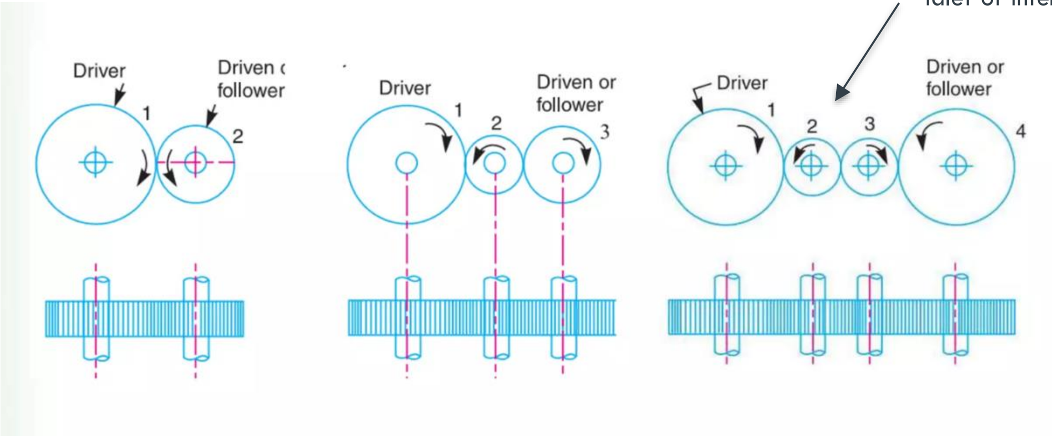
- BionicOpter
  - This video from that page zooms in showing how to use a gear train to
    - Amplify the motor torque or speed
    - Change the direction of rotation of the motor output
    - Change the angle of the rotation axis of the motor output
    - Change continuous motion to periodic or oscillatory motion
    - Use gears to enable a motor to actuate more than one output.
    - Also, the tail illustrated another form of actuation.



Simple Gear Train

- There is only one gear on each shaft
- The number of teeth on a gear is proportional to its radius.
- There is no slip between the gears
- N = number of teeth, r=radius of gear, ω=angular velocity of the gear, v=velocity of a point of contact between 2 gears, T=torque provided by a gear

idler or intermediate gears



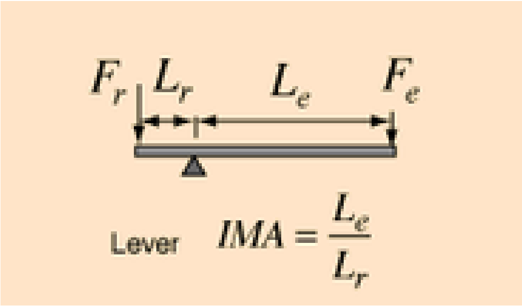
idler or intermediate gears move the output location or change the rotation direction.

$$v = \omega_1 r_1 = \omega_2 r_2$$

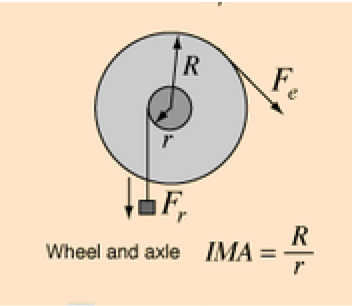
$$\text{mechanical advantage} = \frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} = \frac{N_2}{N_1} = \frac{T_2}{T_1}$$

Recall Mechanical Advantage

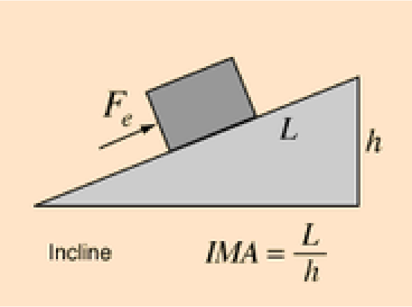
- work = force x distance (W=Fd)
  - Conservation of Work states that $F_1d_1 = F_2d_2$
  - We can "leverage" this principle to generate large forces (or speeds) from small forces (or speeds) to provide the desired ***Mechanical Advantage***.



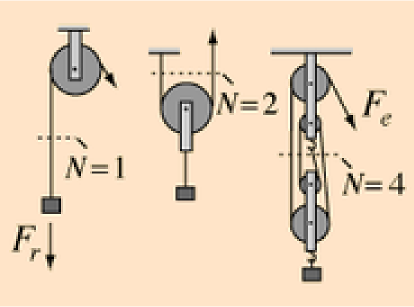
Lever



Wheels/Gears



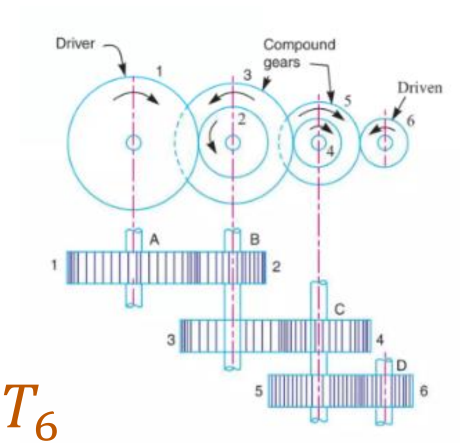
Ramp

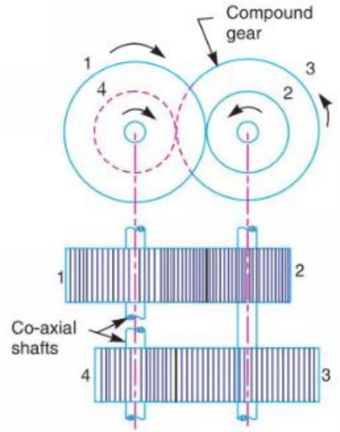


Pulley System, etc.

Common gear trains

- **Compound gear train**: There is more than one gear on each shaft
- **Reverted Gear train**: first and last gear are on the same shaft





$$\frac{N_1}{N_4} = \frac{T_2 T_4}{T_1 T_3}$$

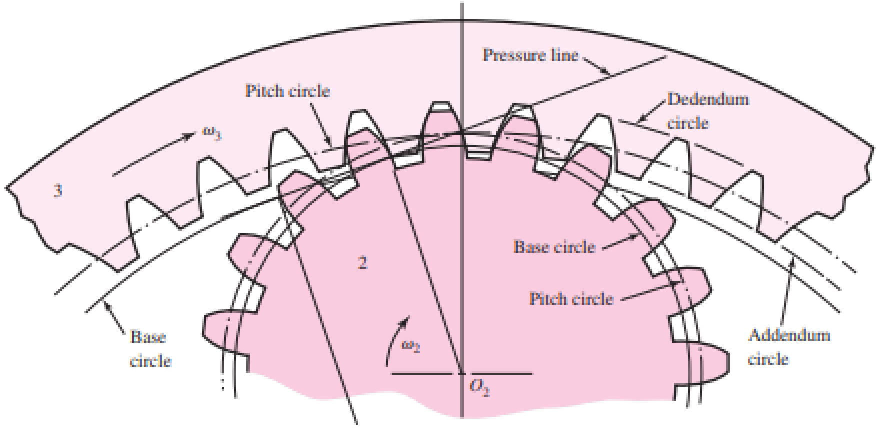
$$\frac{N_1}{N_6} = \frac{T_2 T_4 T_6}{T_1 T_3 T_3}$$

$$N_1 + N_2 = N_3 + N_4$$

How few teeth can I put on a gear?

- Typical tooth shape is *involute*.
- You can’t make a gear with one (or even just a few) teeth!
- You can make a gear with a lot of teeth, but they might sheer
  - Exception harmonic drives
- Answering this correctly is multiple lectures in an ME Engineering component design book
  - We discuss here since students who only learn ratios may look for impossible things

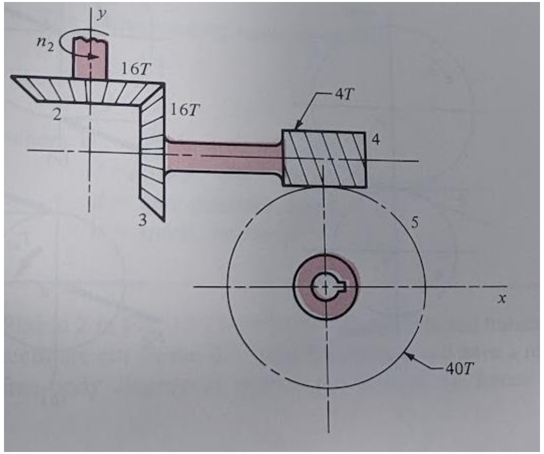
- As a rule of thumb, a single stage gear can have a value up to 10:1
- To minimize package size, keep the ratios in each stage as close as possible
- As a (very loose) rule of thumb, for a safe pressure angle of 20°, the minimum number of teeth on a gear is 16.



https://pollev.com/robertomartinmartin739

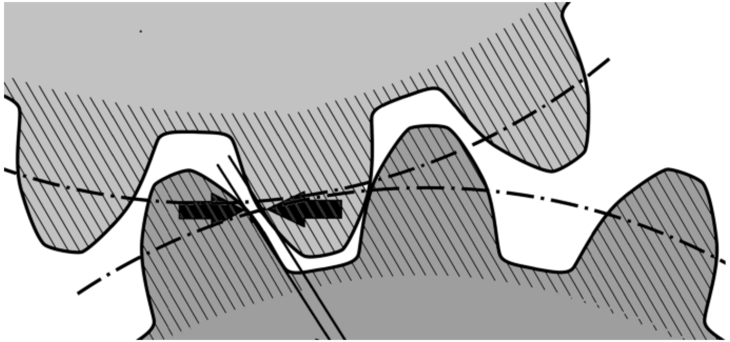
Exercise

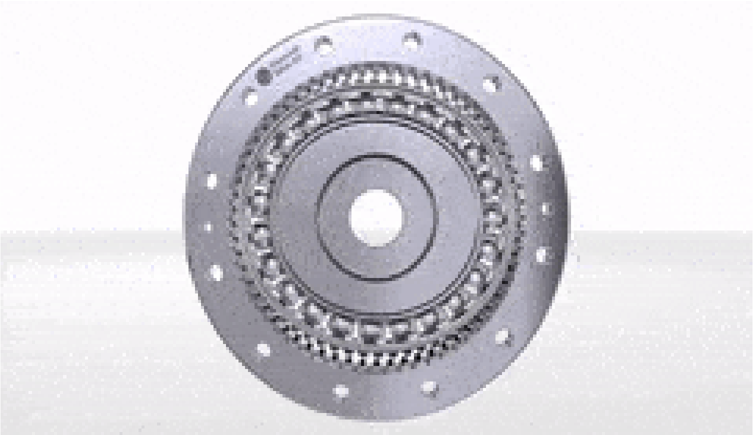
- Example: A gear train with mitre gears (i.e., bevel gears with MA=1) have 16 teeth each and a 4-tooth (right-hand) worm gear interacts with a gear with 40 teeth. If the input n_2=200 rev/min (counterclockwise), what is the speed of the last gear? What is the Mechanical advantage? How could you modify the first bevel if you wanted the speed to stay the same?



Backlash

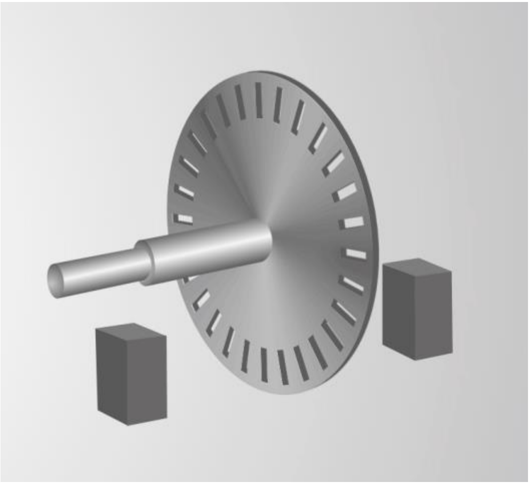
- Cheap, worn out or misaligned gears can create *backlash*.
- Backlash can cause issues with positioning error, vibrations, early wear and inability to apply desired forces.
- Some backlash is necessary (space for lubrication, minimize friction, etc.)
- Harmonic gear trains are popular as they minimize backlash.
- Eliminating backlash is also part of the motivation for *direct drive* robotic actuators.



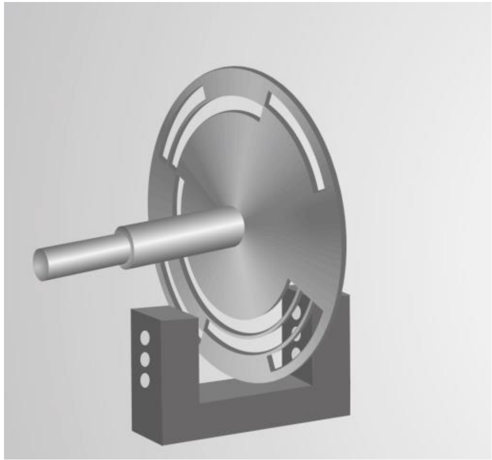


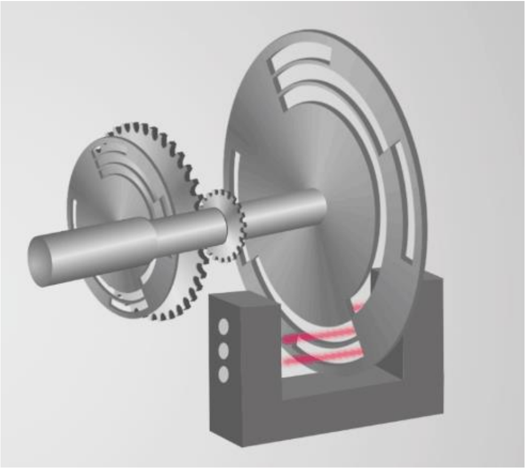
How far has my actuator turned?

- Relative Encoders



- Absolute Encoders (single/multi turn)

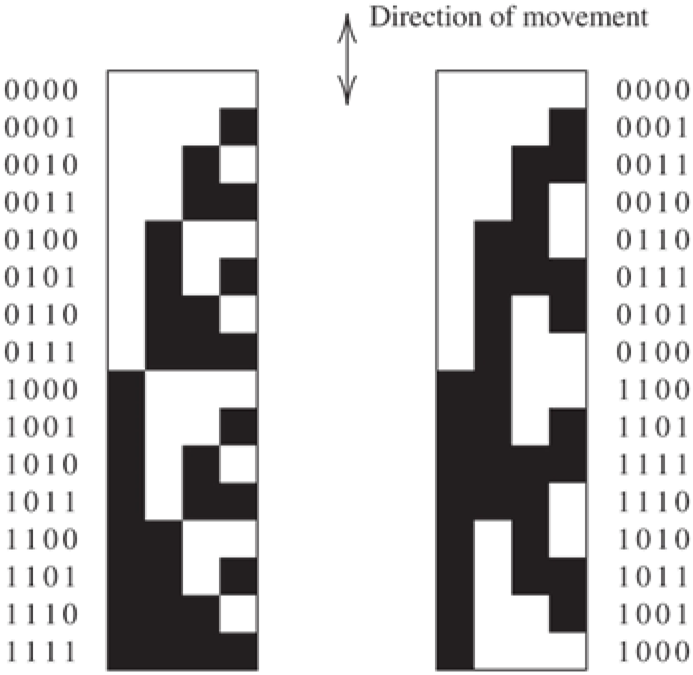




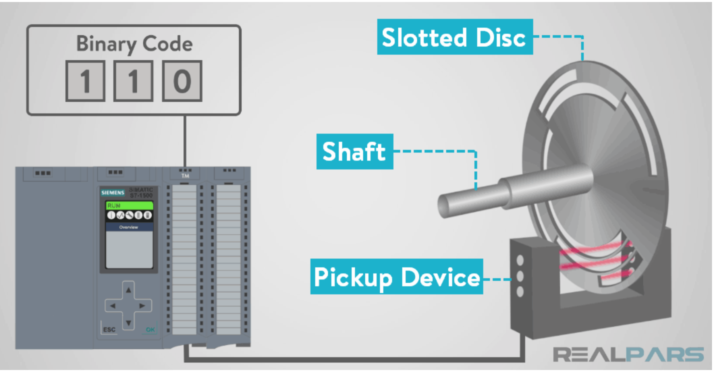
- Encoder: sensor that measures the “amount of rotation” in my actuator (there also linear encoders for linear actuators)
- Encoders may utilize magnetic, optical, inductive, capacitive, or laser signals
- The type of sensor impacts precision, cost, durability, system integration, etc.
- Some high-end actuators have encoders on both the input and output to account for actuator deflections and backlash.

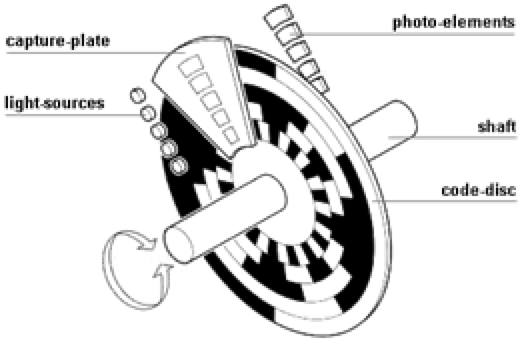
https://realpars.com/absolute-vs-incremental-encoder/

Encoding: Binary vs Gray (to avoid hazards)



(a) Binary code (b) Gray code





Gray code: Successive code words change by only 1 bit

Conclusions

- Actuator: The core robot component that converts power to controlled motion.
- The key actuator elements are
  - Motor, Gear train, Encoder
- Characterizing actuators: torque-speed diagram
- Types of actuators
- Next up: How do we control actuators?