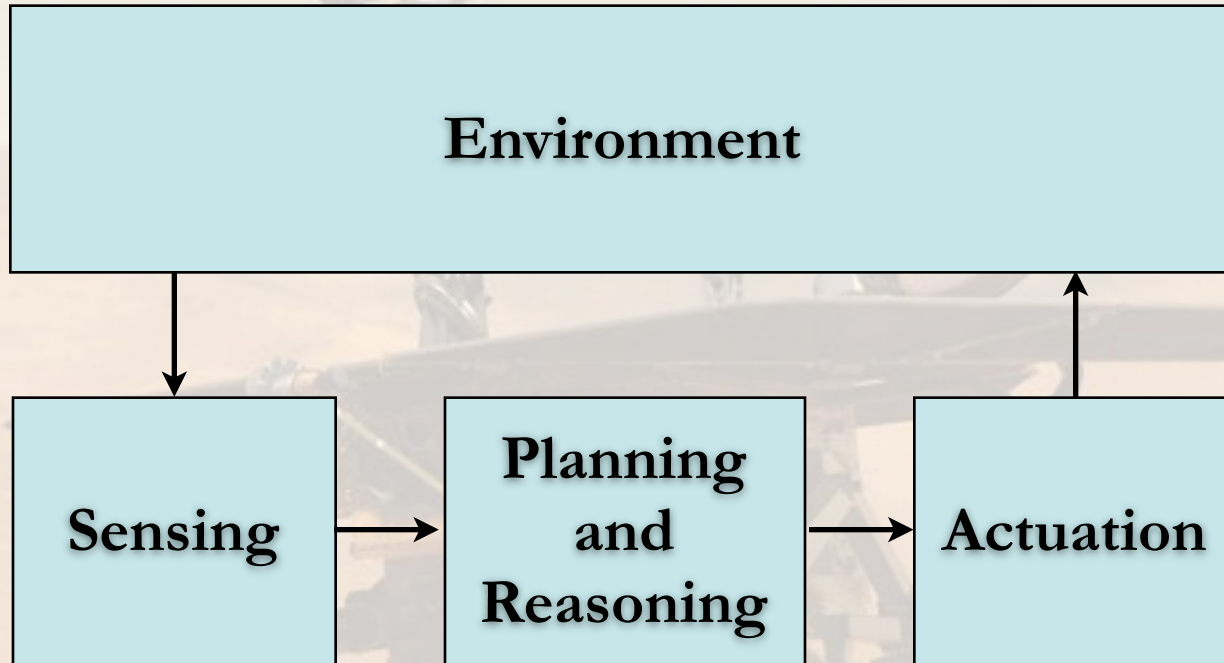


# Actuator Components

- Actuators
  - Hydraulics
  - Pneumatics
  - Electric Motors
- Gearing
- Bearings
- Seals



# Fundamental Elements of Robotics

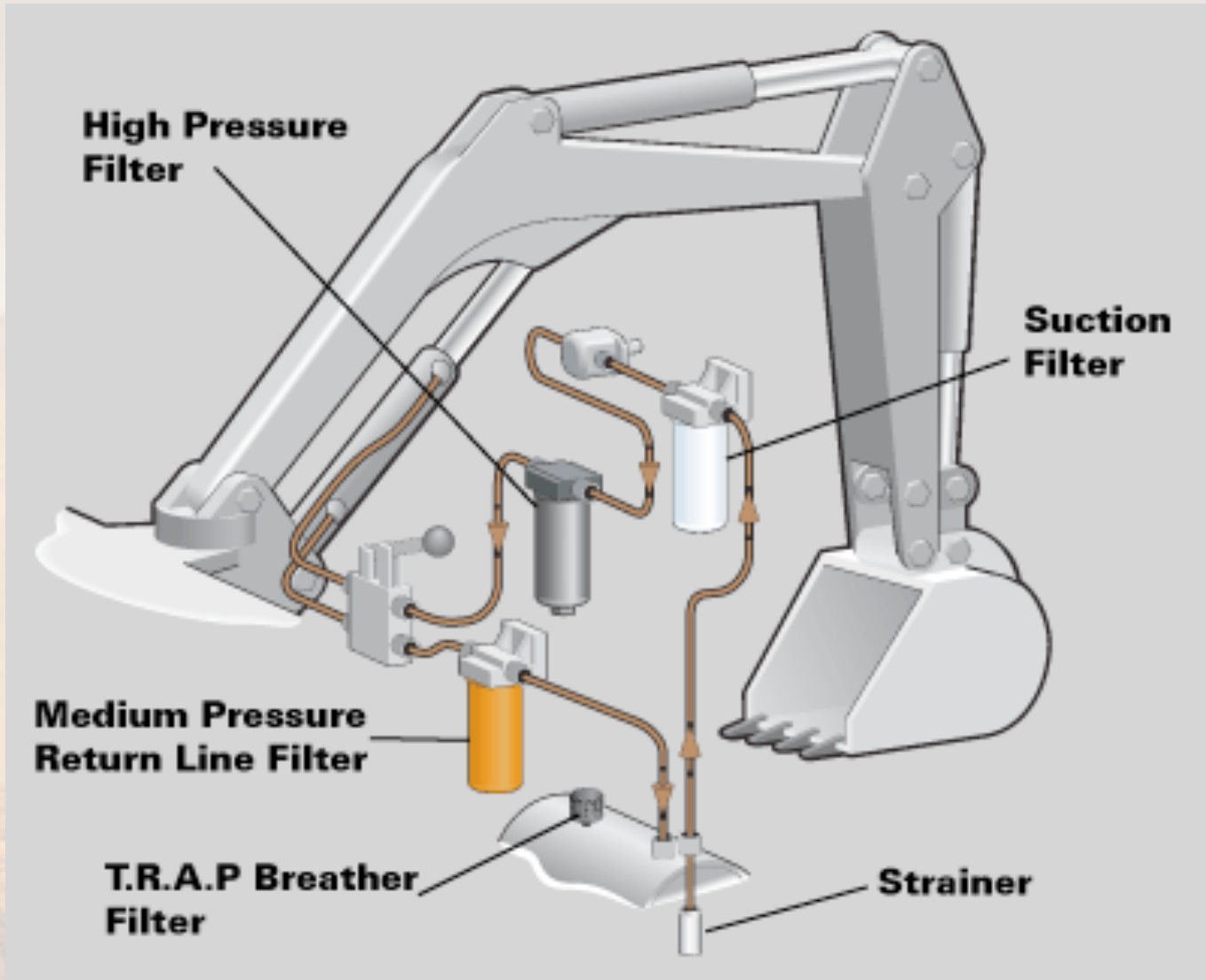


# Prime Mover Taxonomy

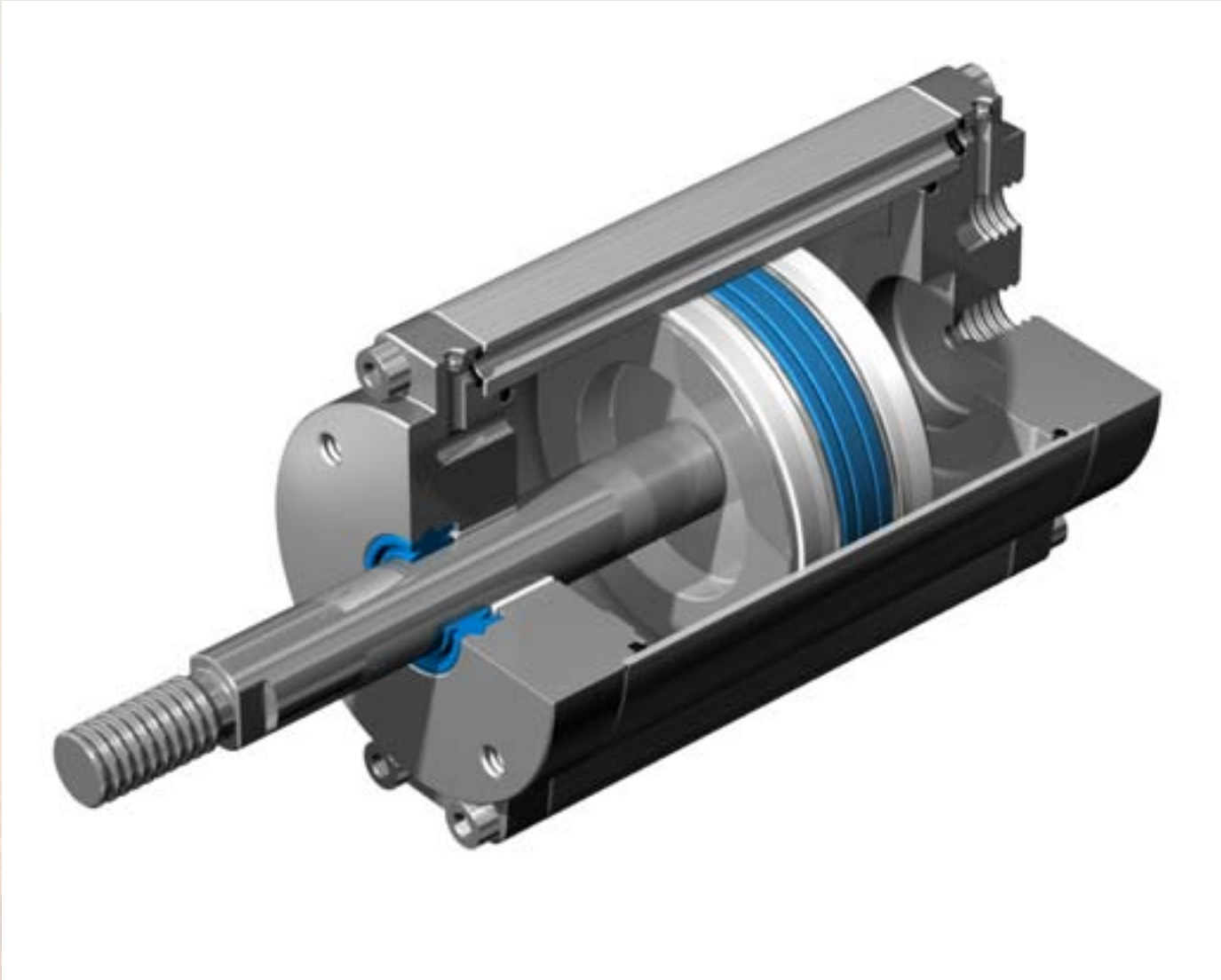
- Electrical
  - Direct Current
  - Alternating Current
- Non-Electrical
  - Hydraulics
  - Pneumatics
  - Chemical
  - Thermal
  - Stored Energy



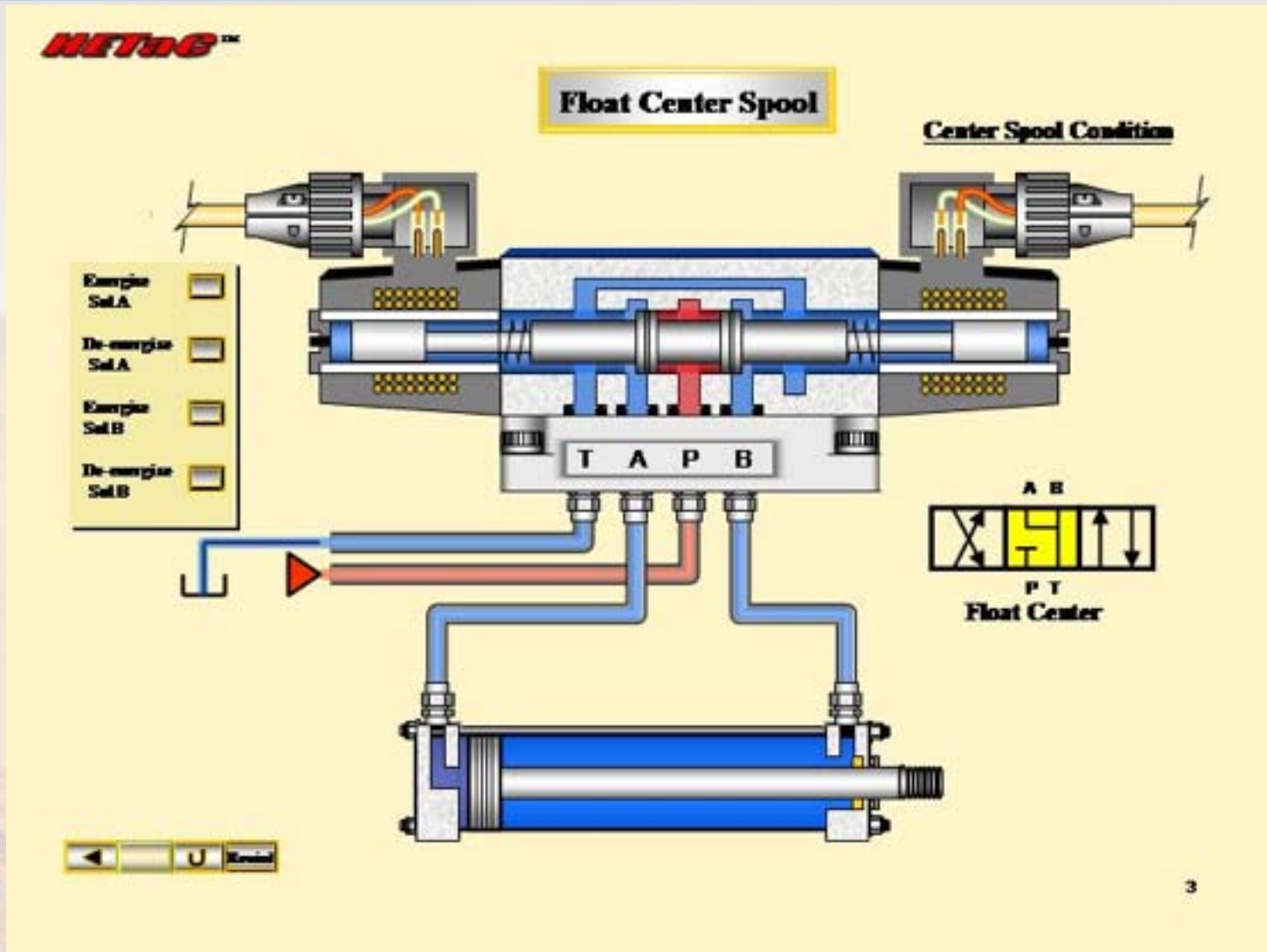
# Hydraulics and Pneumatics



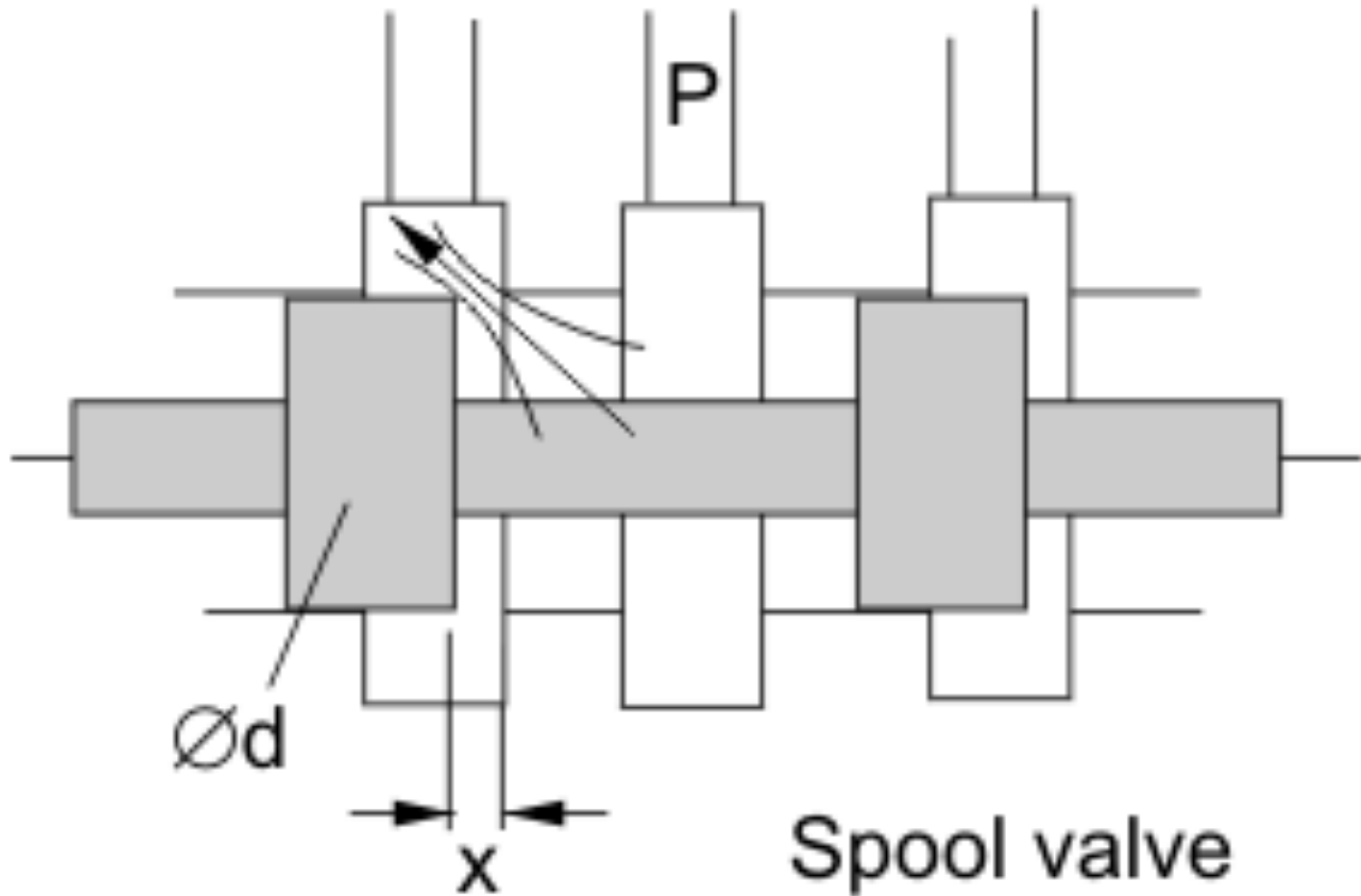
# Pneumatic Actuator Cutaway



# Hydraulic System Schematic

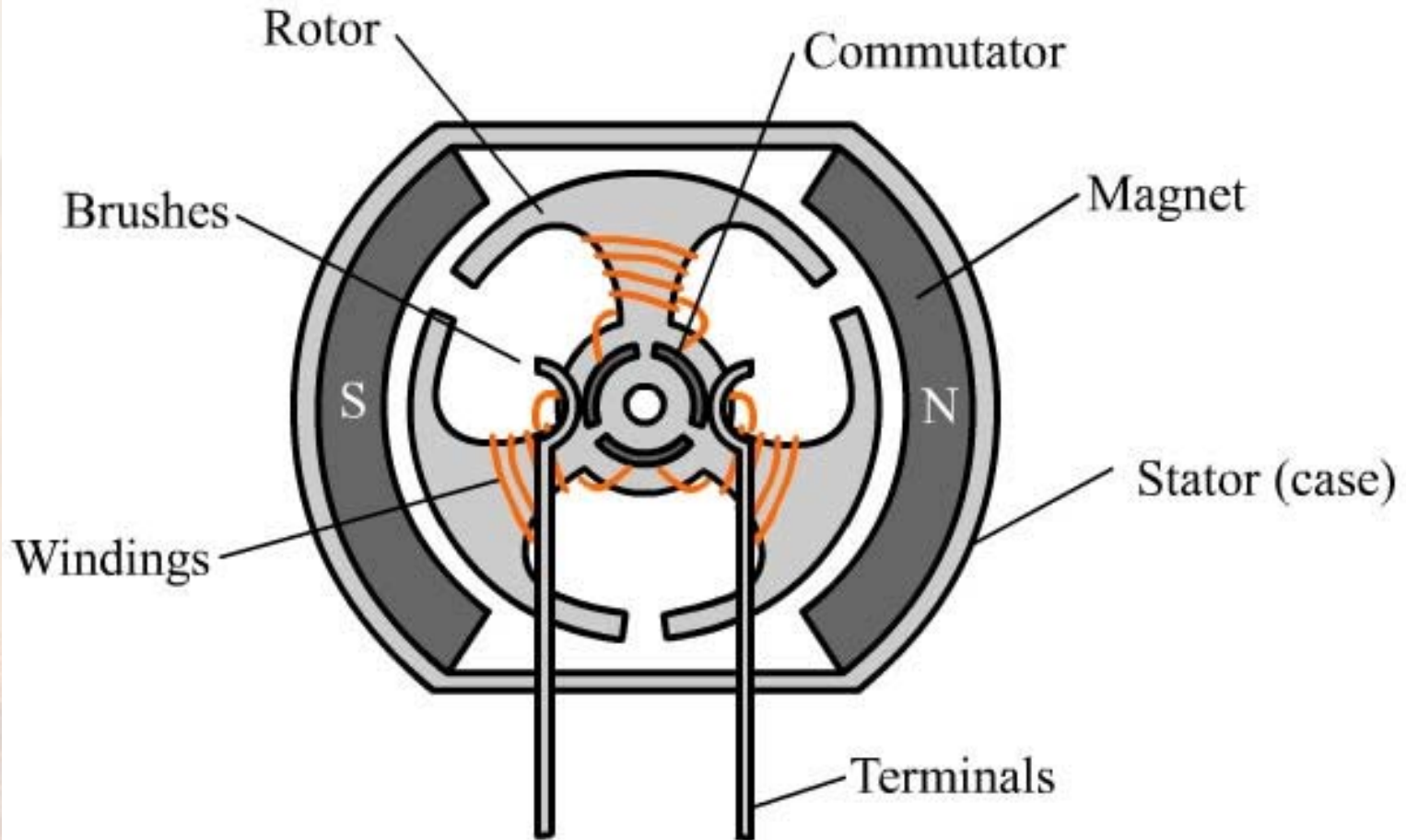


# Hydraulic Spool Valve Schematic



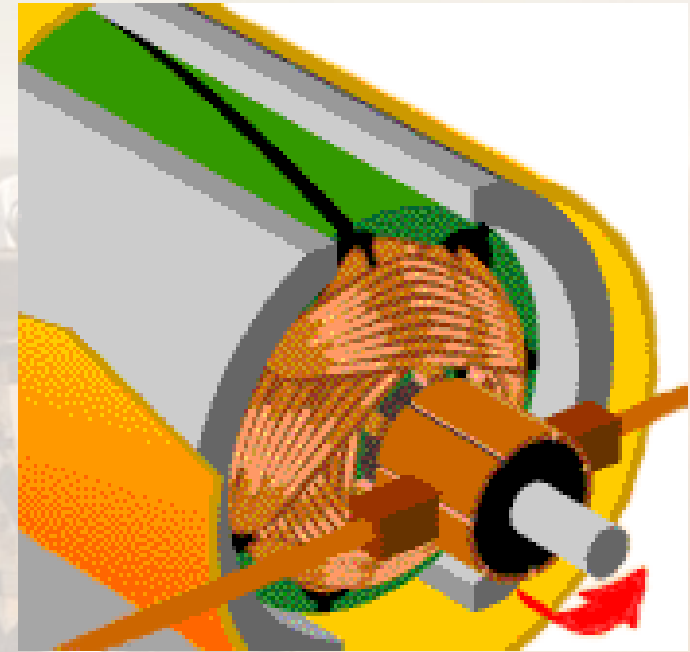
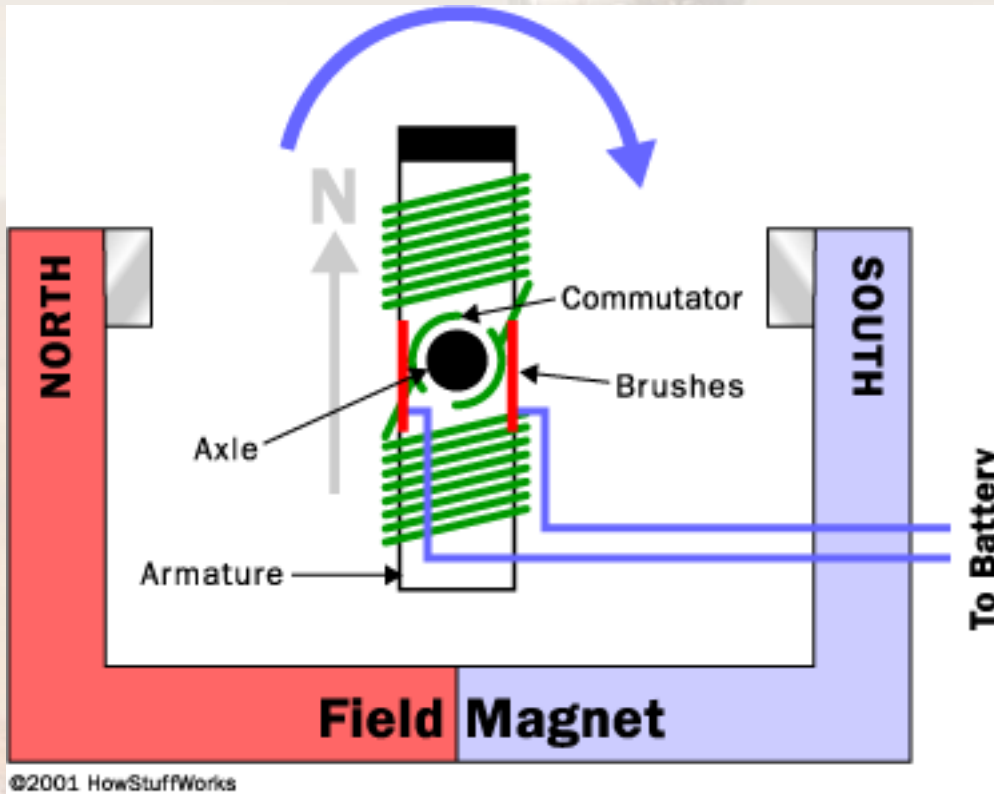
# Brushed DC Motor Schematic

Typical Brushed Motor in Cross-section

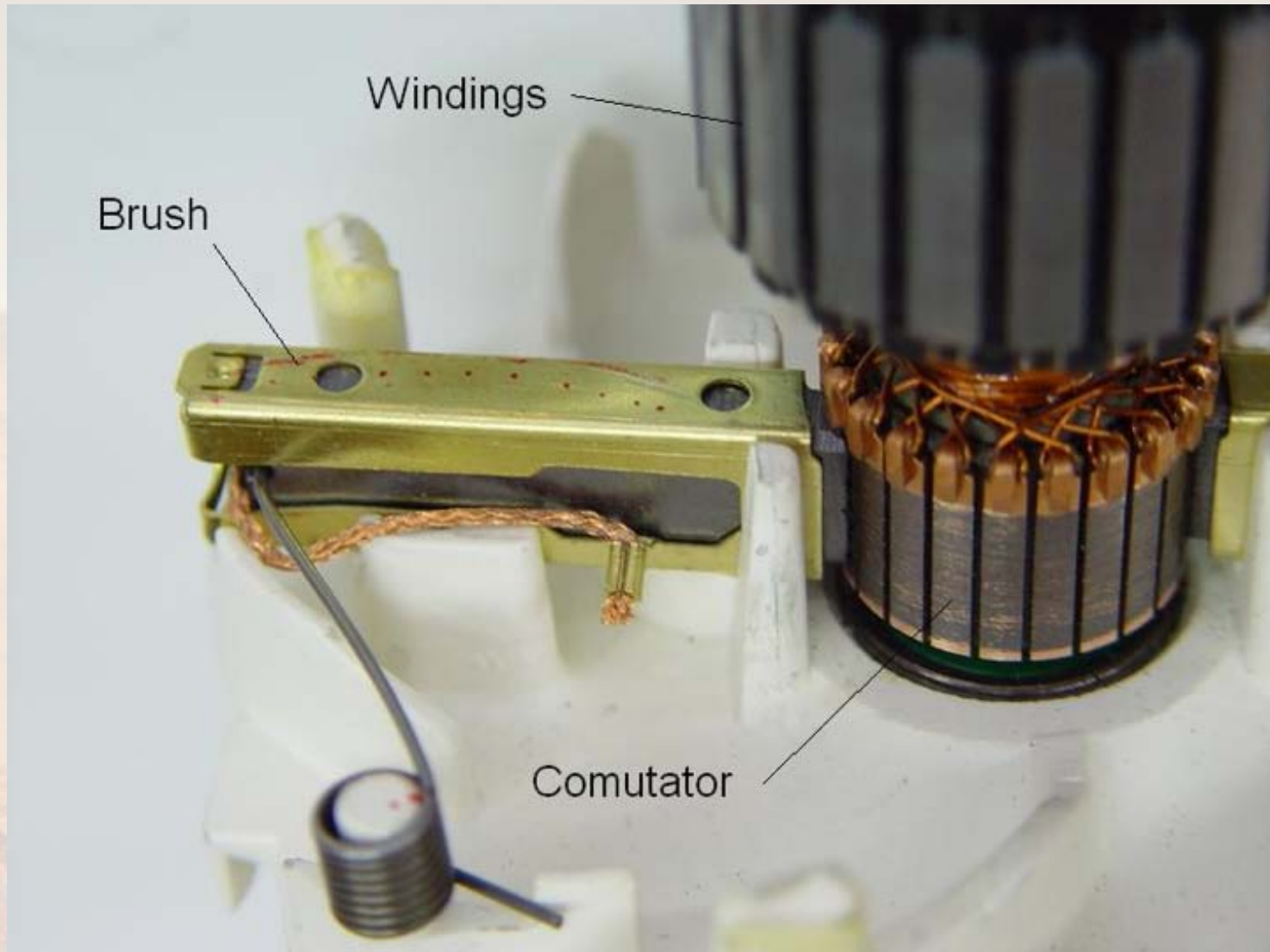




# DC Brushed Motor Schematic



# Brushed DC Motor Commutator



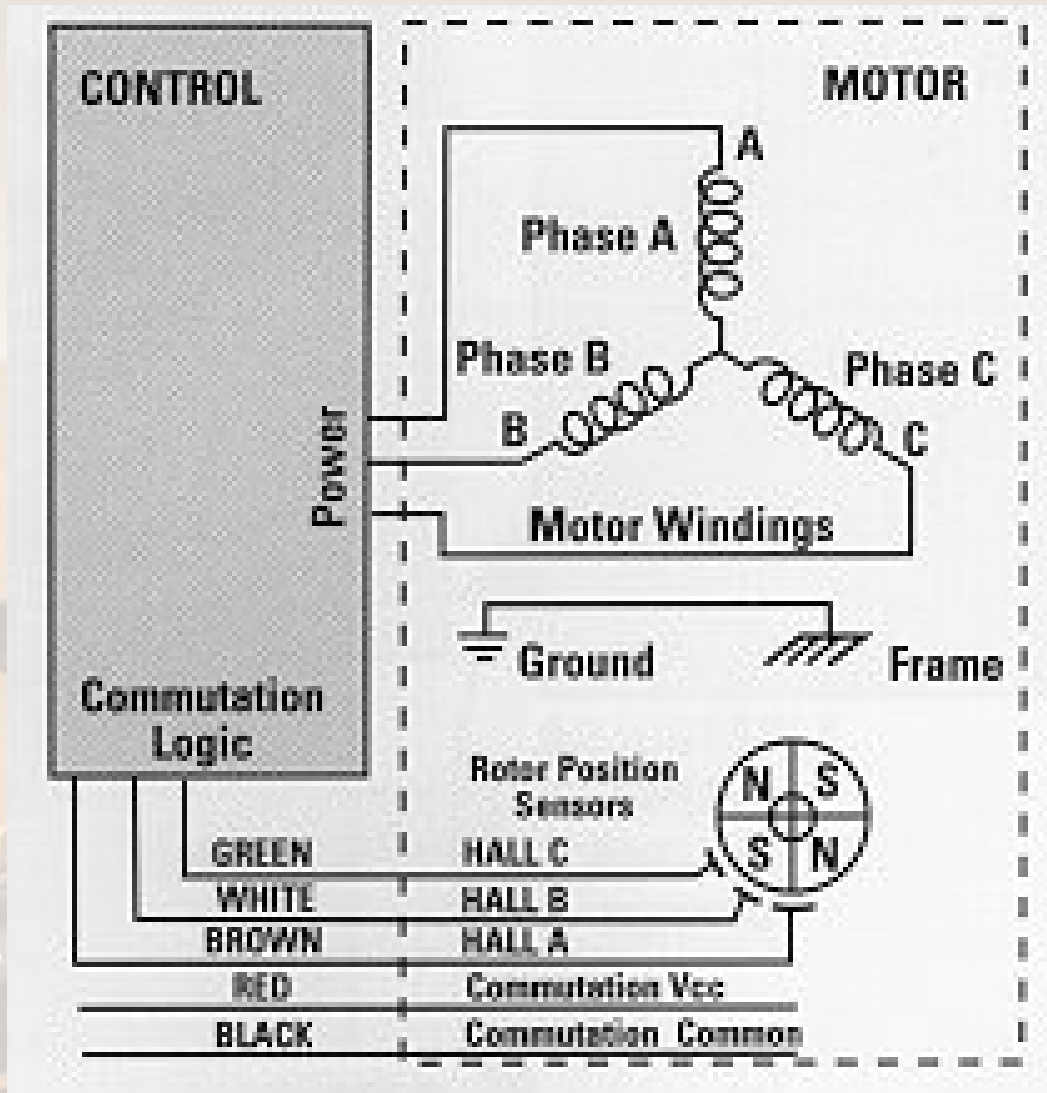
# Brushless DC Motor



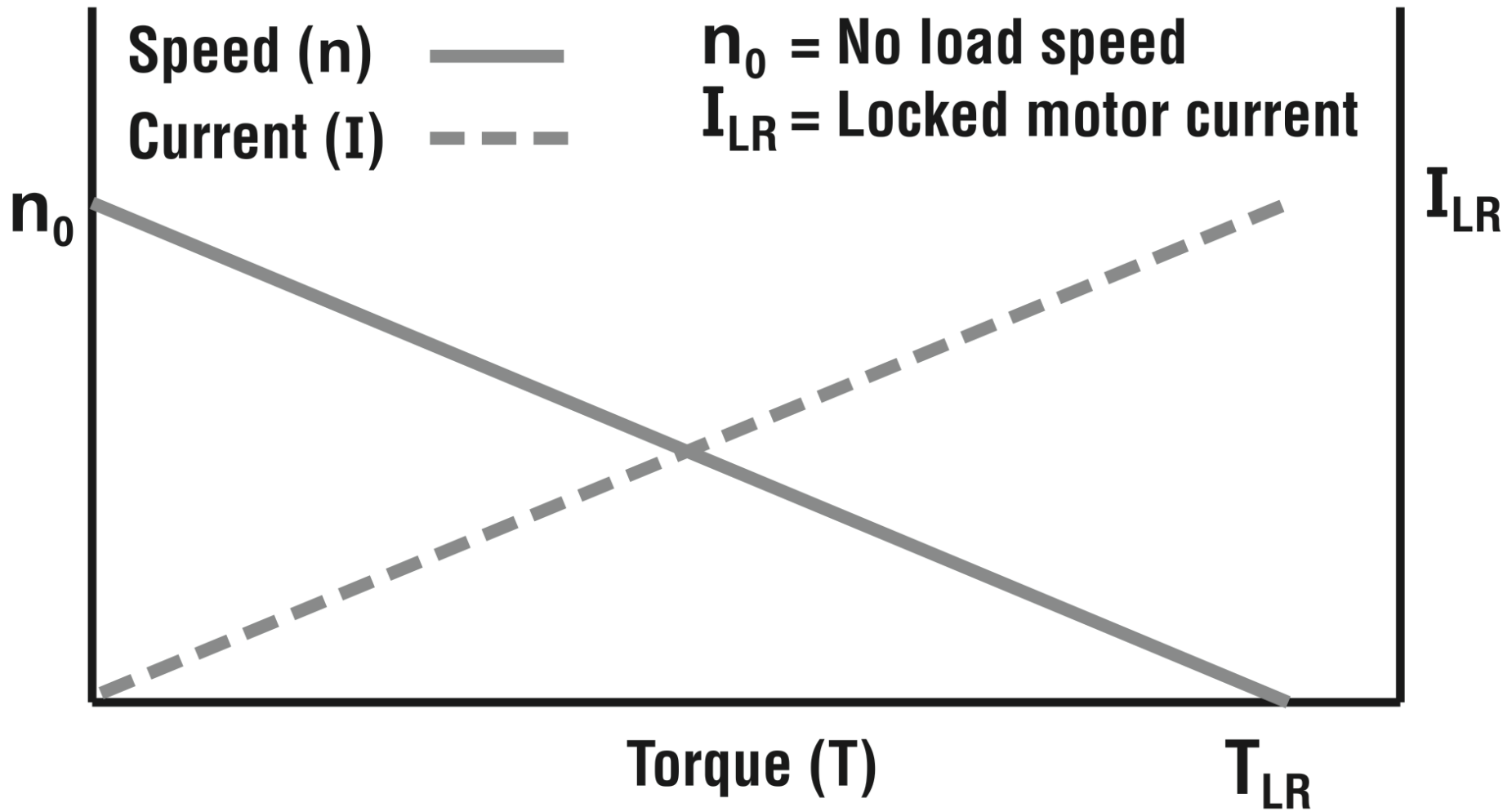
# Brushless Outrunner Motor



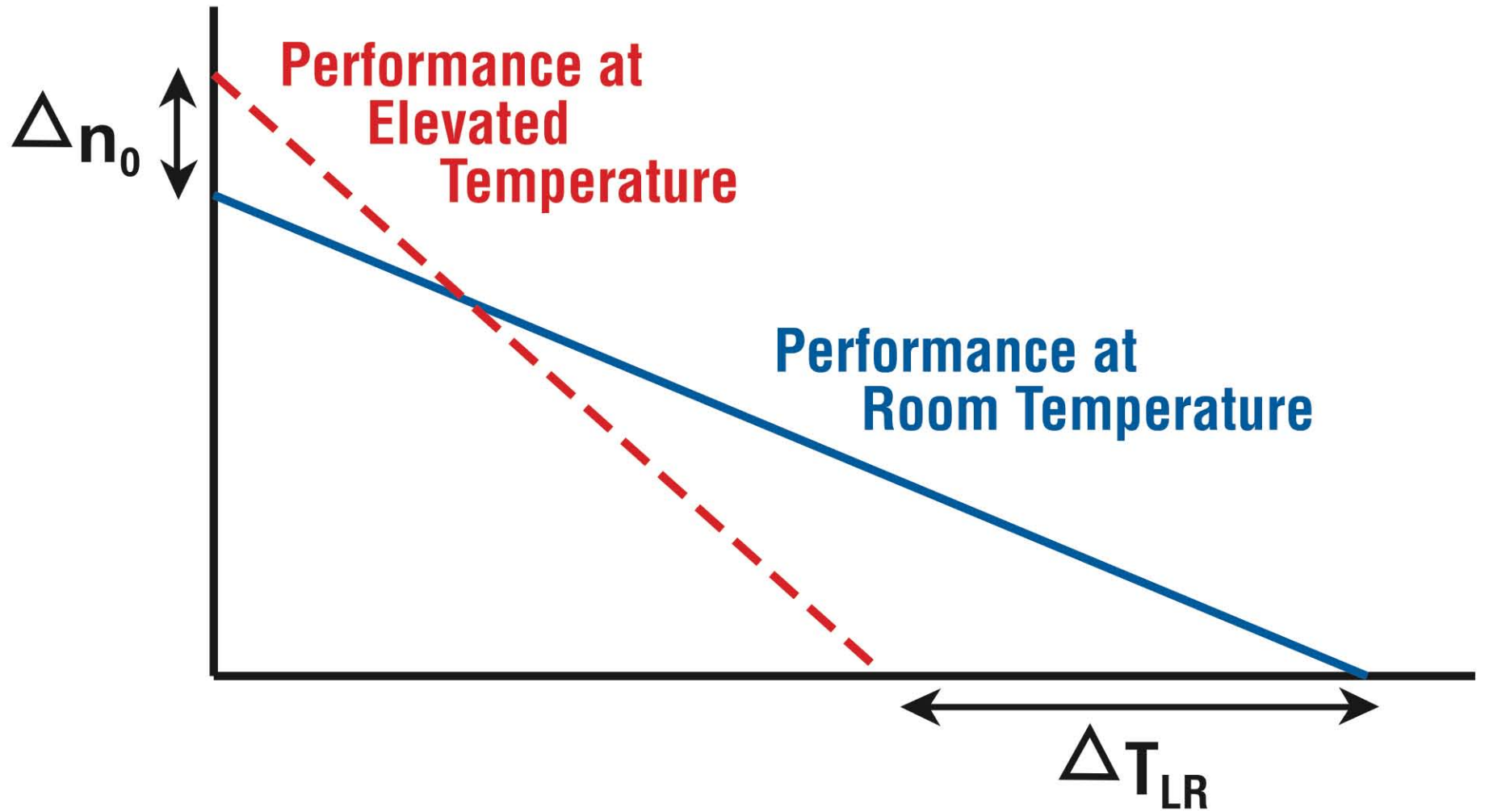
# DC Brushless Motor Schematic



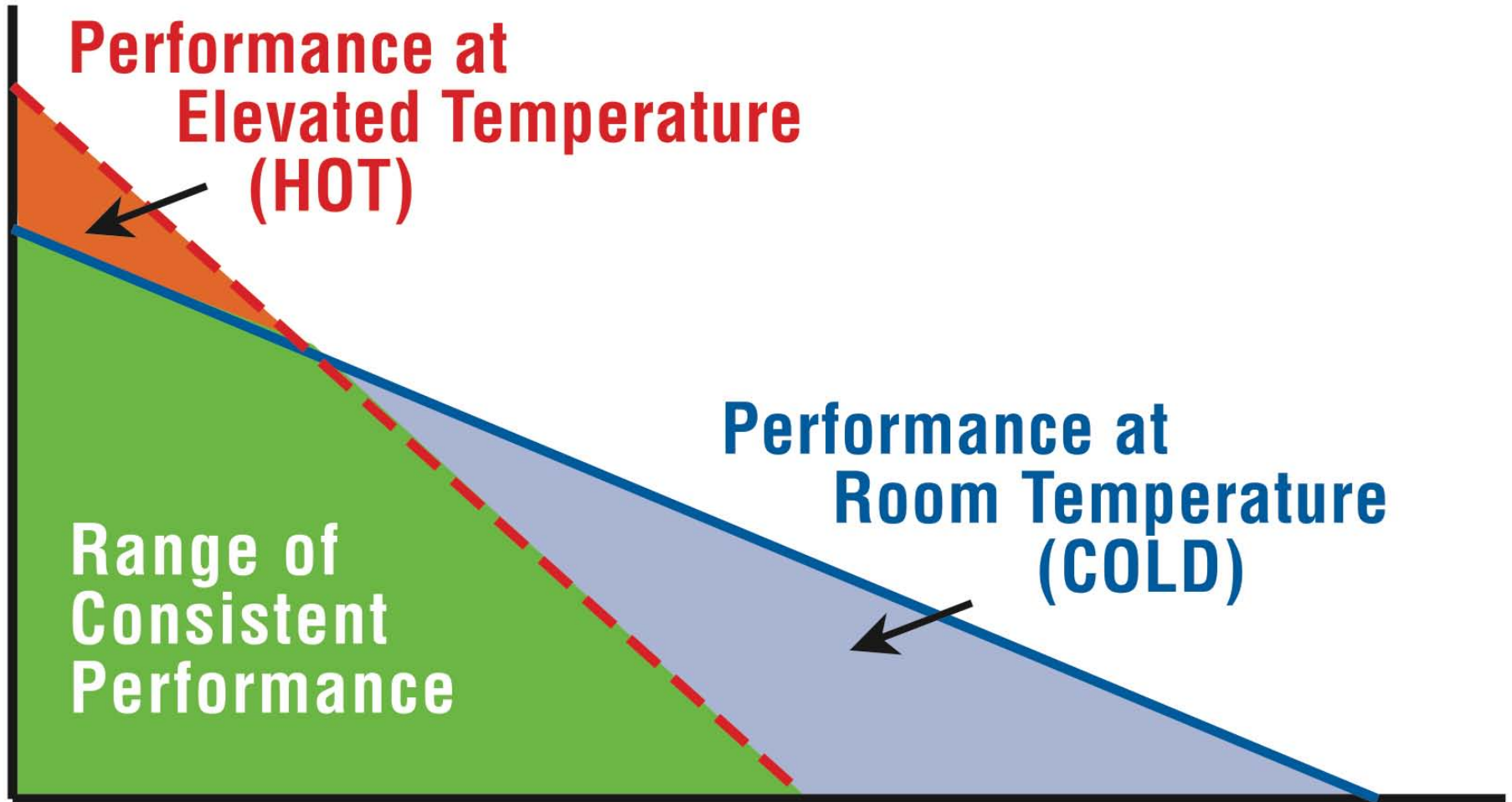
# Basic DC Motor Drive Characteristics



# Effects of Temperature on DC Motors

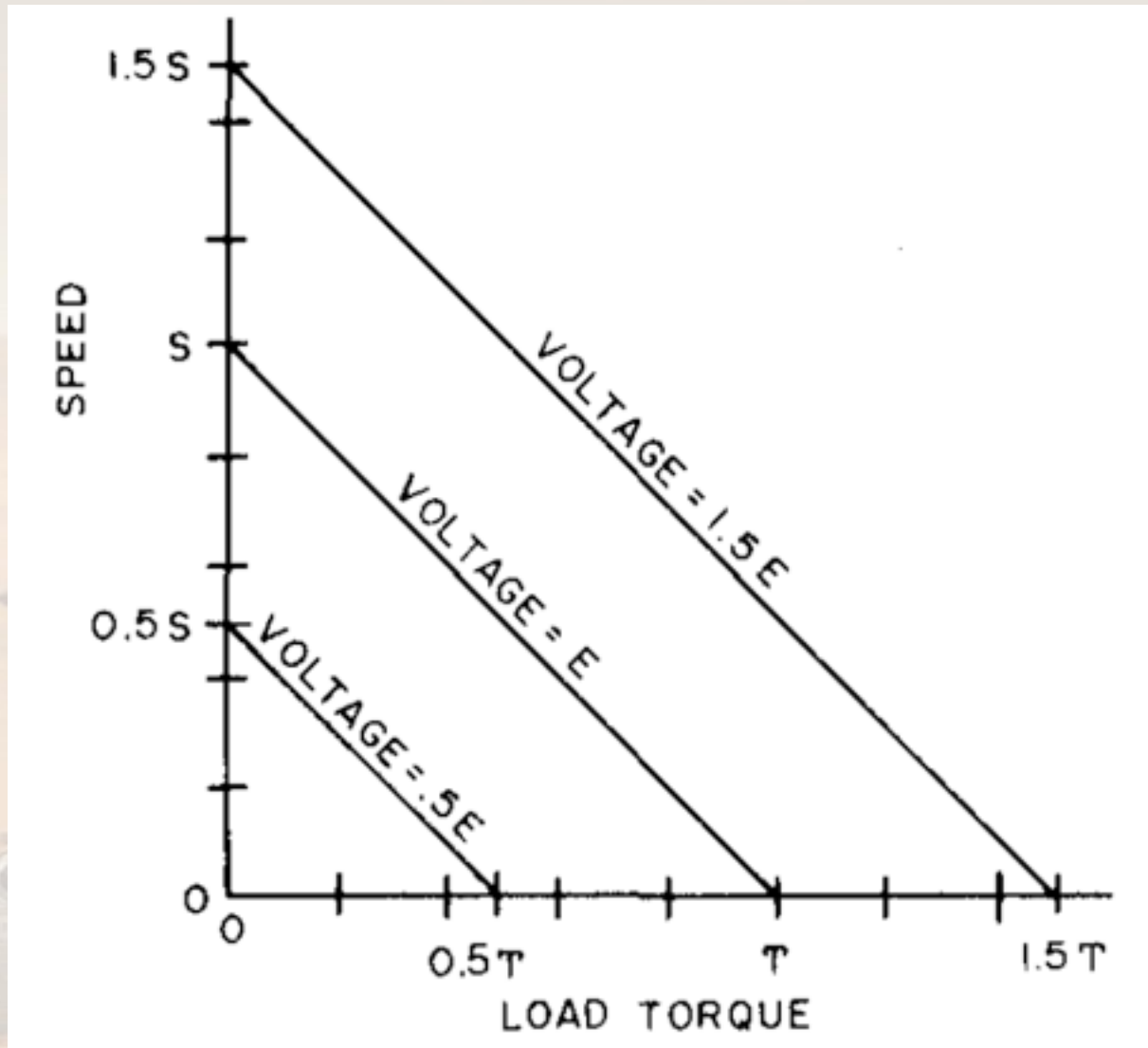


# Effects of Temperature on DC Motors

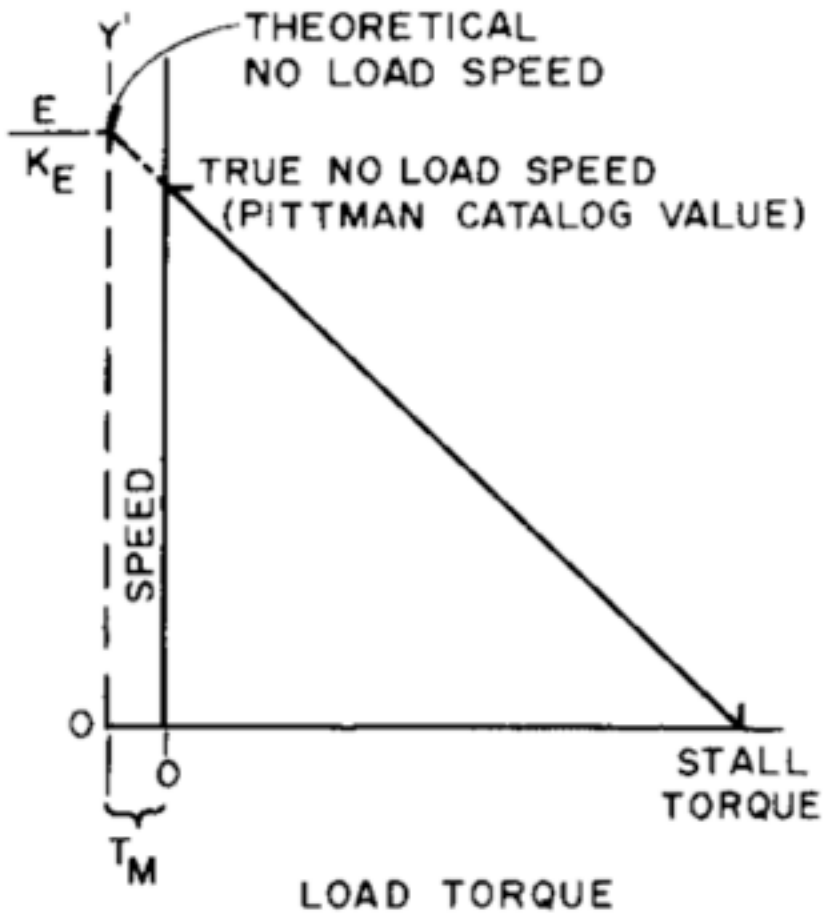




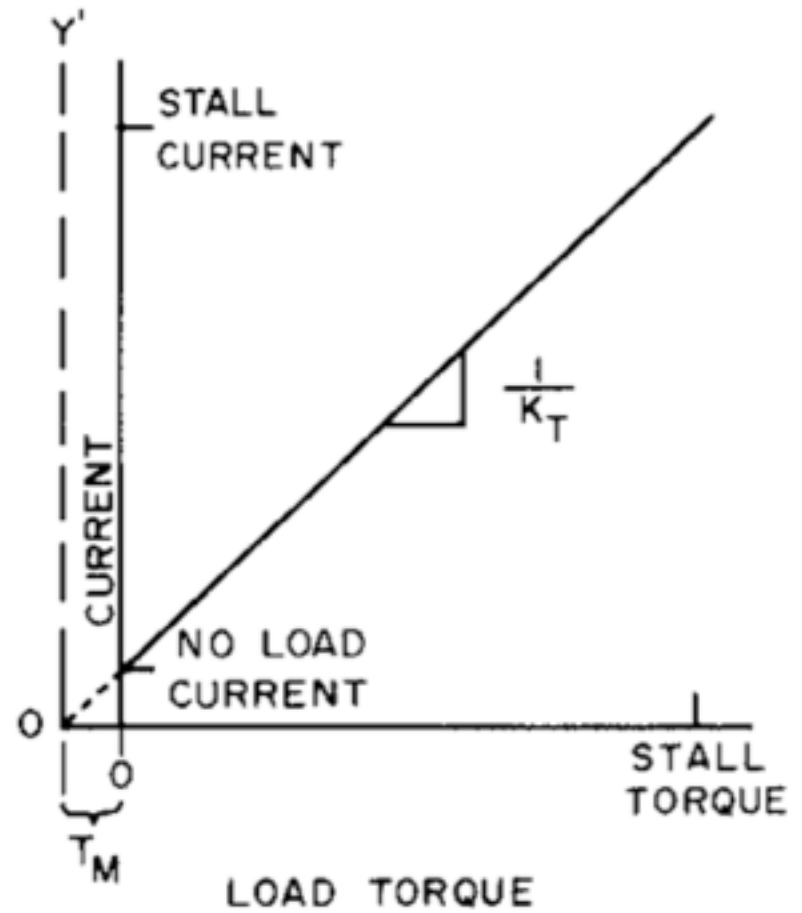
# Speed as a Function of Torque



# Standard DC Motor Characteristics



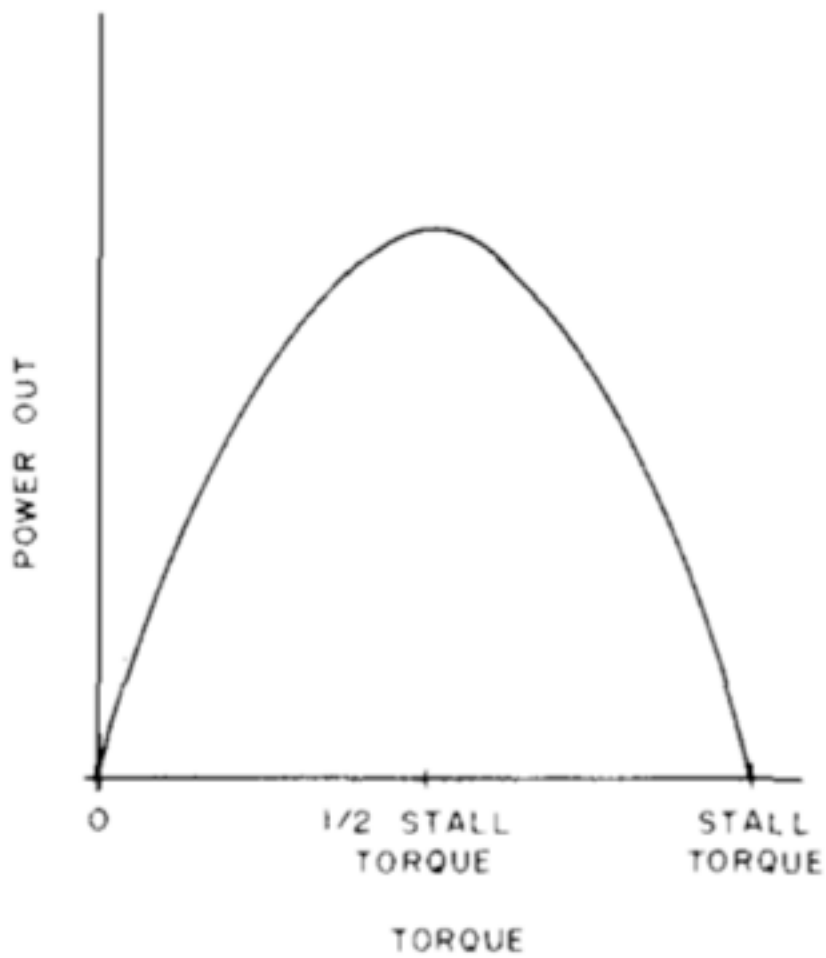
a) Speed vs. Torque



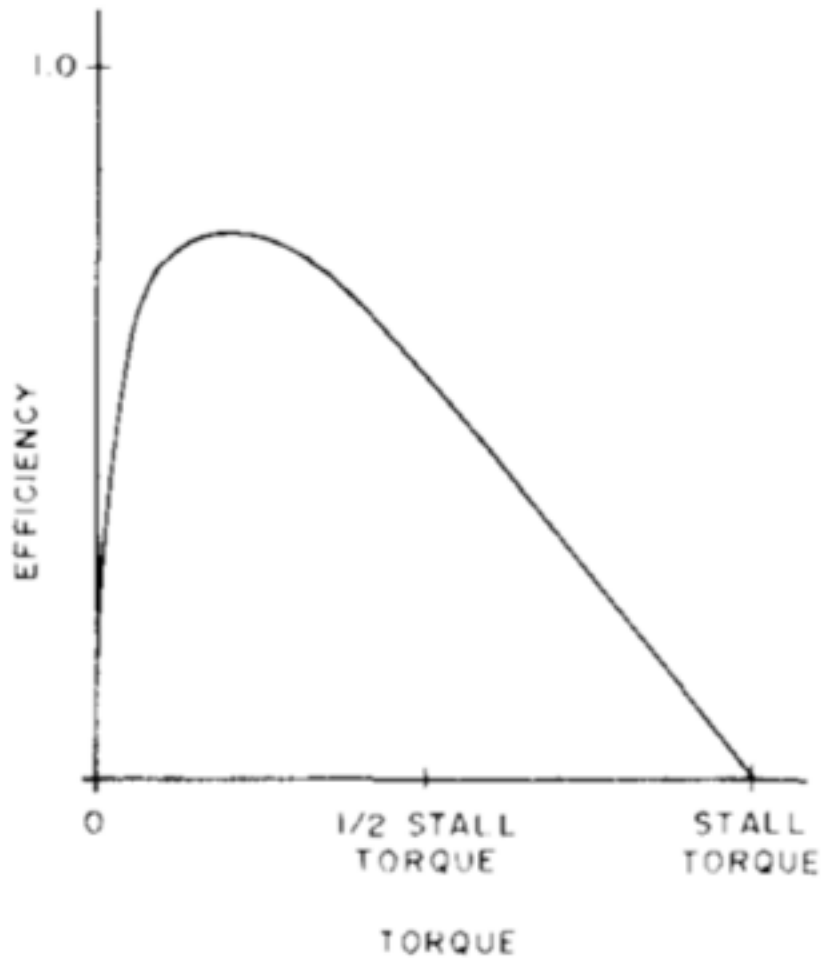
b) Current vs. Torque



# DC Motor Power and Efficiency




a) Power Out



b) Efficiency



# Typical DC Motor Specification

Winding types		-216P	-216E
<b>Measured values</b>			
1 Measuring voltage	V	3.0	6.0
2 No-load speed	rpm	5200	5600
3 Stall torque	mNm (oz-in)	10.9 (1.54)	10.6 (1.50)
4 Average no-load current	mA	26	16
5 Typical starting voltage	V	0.25	0.35
<b>Max. recommended values</b>			
6 Max. continuous current	A	1.50	0.83
7 Max. continuous torque	mNm (oz-in)	8 (1.13)	8.1 (1.15)
8 Max. angular acceleration	$10^3 \text{ rad/s}^2$	62	102
<b>Intrinsic parameters</b>			
9 Back-EMF constant	V/1000 rpm	0.57	1.05
10 Torque constant	mNm/A (oz-in/A)	5.4 (0.77)	10 (1.42)
11 Terminal resistance	ohm	1.5	5.7
12 Motor regulation $R/k^2$	$10^3/\text{Nms}$	51	57
13 Rotor inductance	mH	0.10	0.35
14 Rotor inertia	$\text{kgm}^2 \cdot 10^{-7}$	3.5	2
15 Mechanical time constant	ms	18	11



# Standard Motor Specifications

Parameter	Typical Symbols	Tolerance	Typical Units
Torque Constant	$K_T$ , TPA	±15%	$\frac{\text{oz}\cdot\text{in}}{\text{A}}$ $\frac{\text{N}\cdot\text{m}}{\text{A}}$
Back emf Constant	$K_E$ , BEF	±15%	$\frac{\text{volts}}{1000\text{rpm}}$ $\frac{\text{volts}}{\text{rad/s}}$
Terminal Resistance	$R_T$ , RTR	±15%	ohms
Inductance	L, DUK	±10%	millihenries
Inertia	J, ERT	±10%	$\text{oz}\cdot\text{in}\cdot\text{s}^2$ , $\text{kg}\cdot\text{m}^2$ , $\text{N}\cdot\text{m}\cdot\text{s}^2$
Motor Torque losses	$T_M$	+30%	$\text{oz}\cdot\text{in}$ , $\text{N}\cdot\text{m}$
Motor Friction	$T_F$ , TOF	+50%	$\text{oz}\cdot\text{in}$ , $\text{N}\cdot\text{m}$
No Load Current	$I_0$ , INL	+30%	amperes

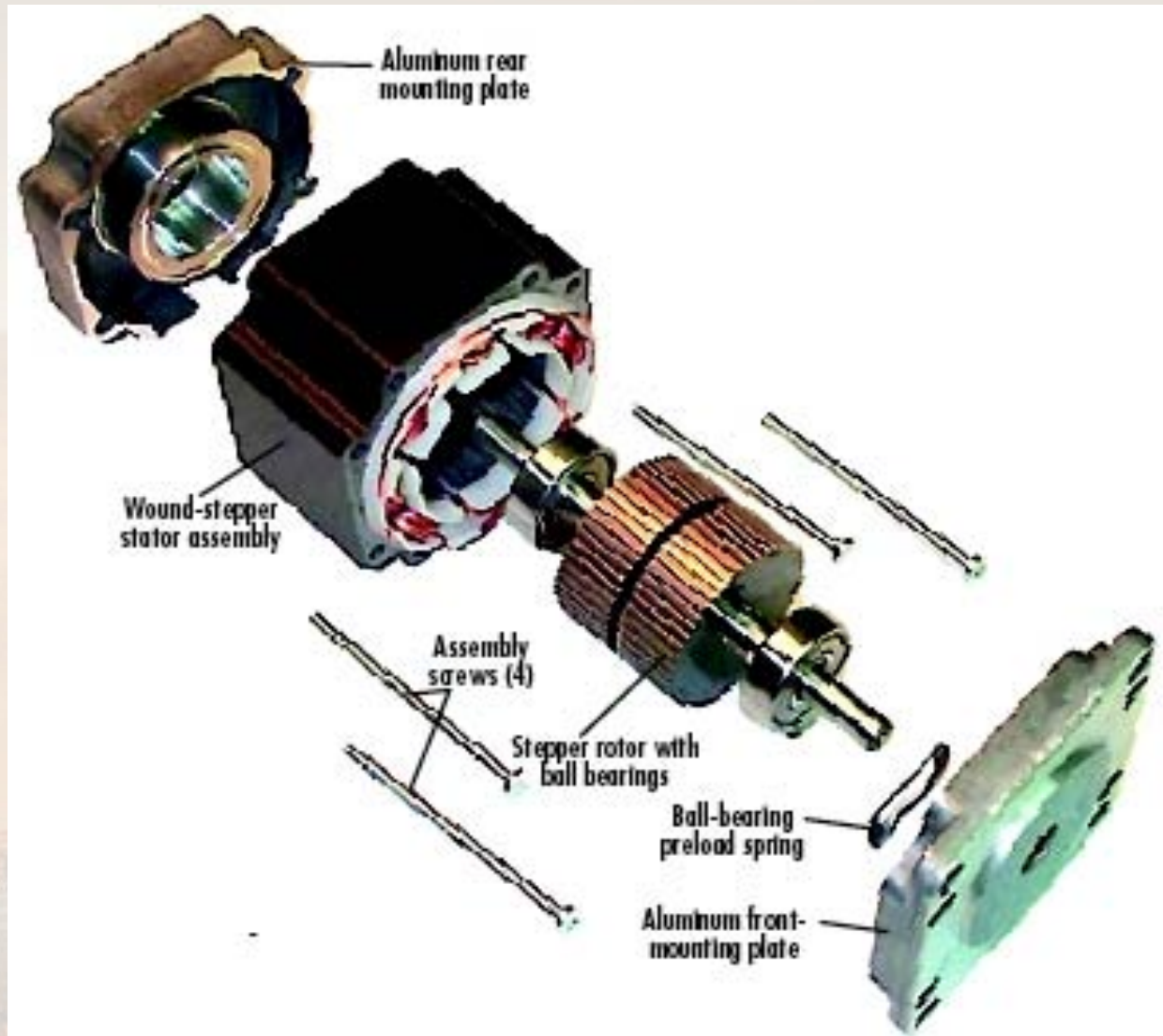
Parameter	Symbols	Tolerance	Derivation	Typical Units
Stall Torque	$T_P$ , TPK	Reference	$\frac{E \times K_T - T_F}{R_T}$	$\text{oz}\cdot\text{in}$ , $\text{N}\cdot\text{m}$
No Load Speed	$\omega_0$ , SNL, $\omega_{NL}$ , $\omega_{NL}$	±15%	$\frac{E - I_{NL} \times R_T}{K_E}$	rpm, rad/s
Stall Current	$I_P$ , AMP	±15%	$E/R_T$	amperes
Motor Constant	$K_M$ , PKO	Reference	$K_T/\sqrt{R_T}$	$\frac{\text{oz}\cdot\text{in}}{\sqrt{\text{W}}}$ $\frac{\text{N}\cdot\text{m}}{\sqrt{\text{W}}}$
Damping Constant (zero source impedance)	$K_D$ , DPO	Reference	$\frac{K_T \times K_E}{R_T}$	$\text{oz}\cdot\text{in}/(\text{rad/s})$ , $\text{N}\cdot\text{m}/(\text{rad/s})$
Electrical Time Constant	$T_E$ , TCE	Reference	$\frac{L}{R_T}$	ms
Mechanical Time Constant	$T_M$ , TCM	Reference	$\frac{J \times R_T}{K_T \times K_E}$ $\frac{J}{K_D}$	ms



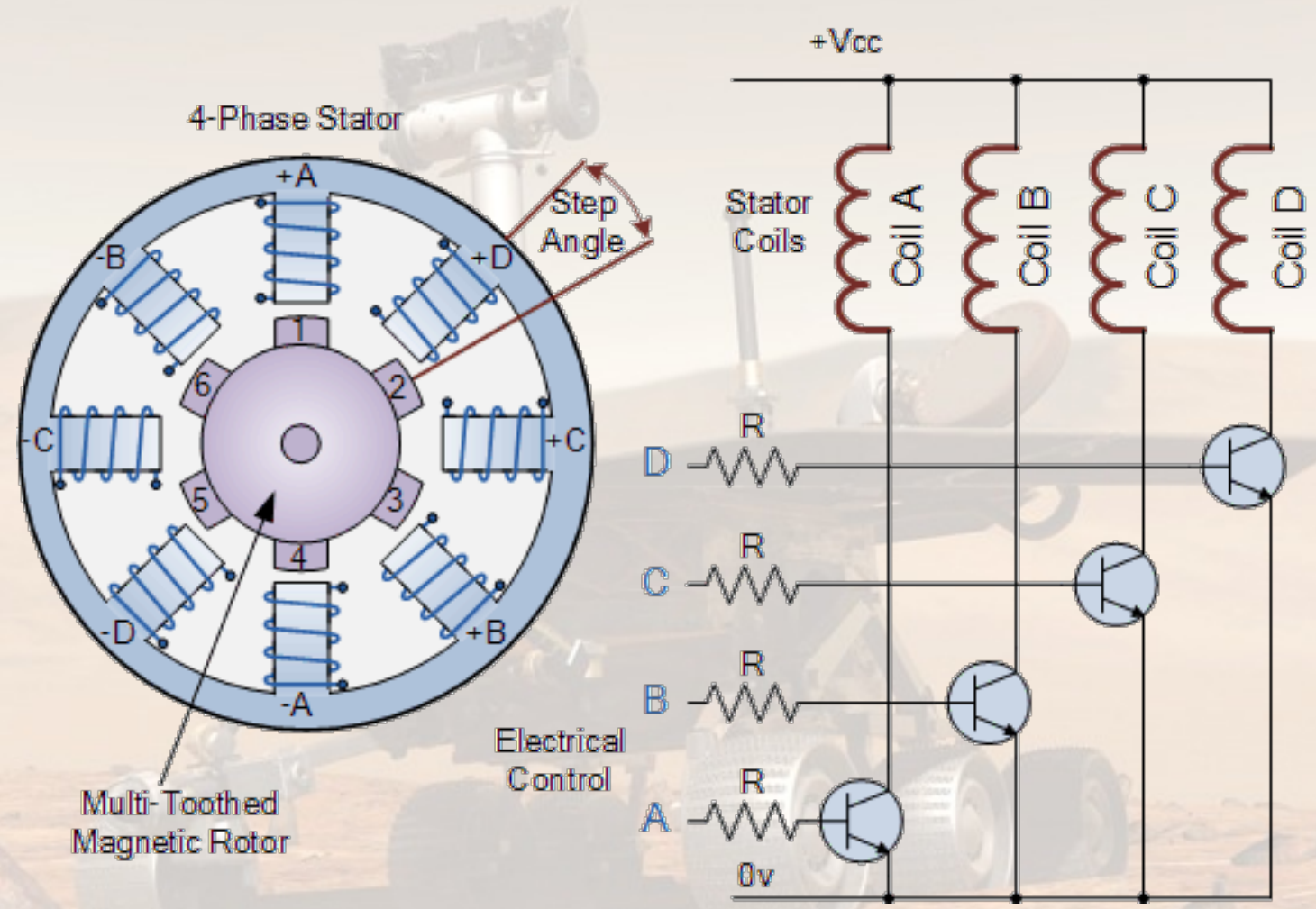
# Axial Flux Motor



# Stepper Motor Exploded Image

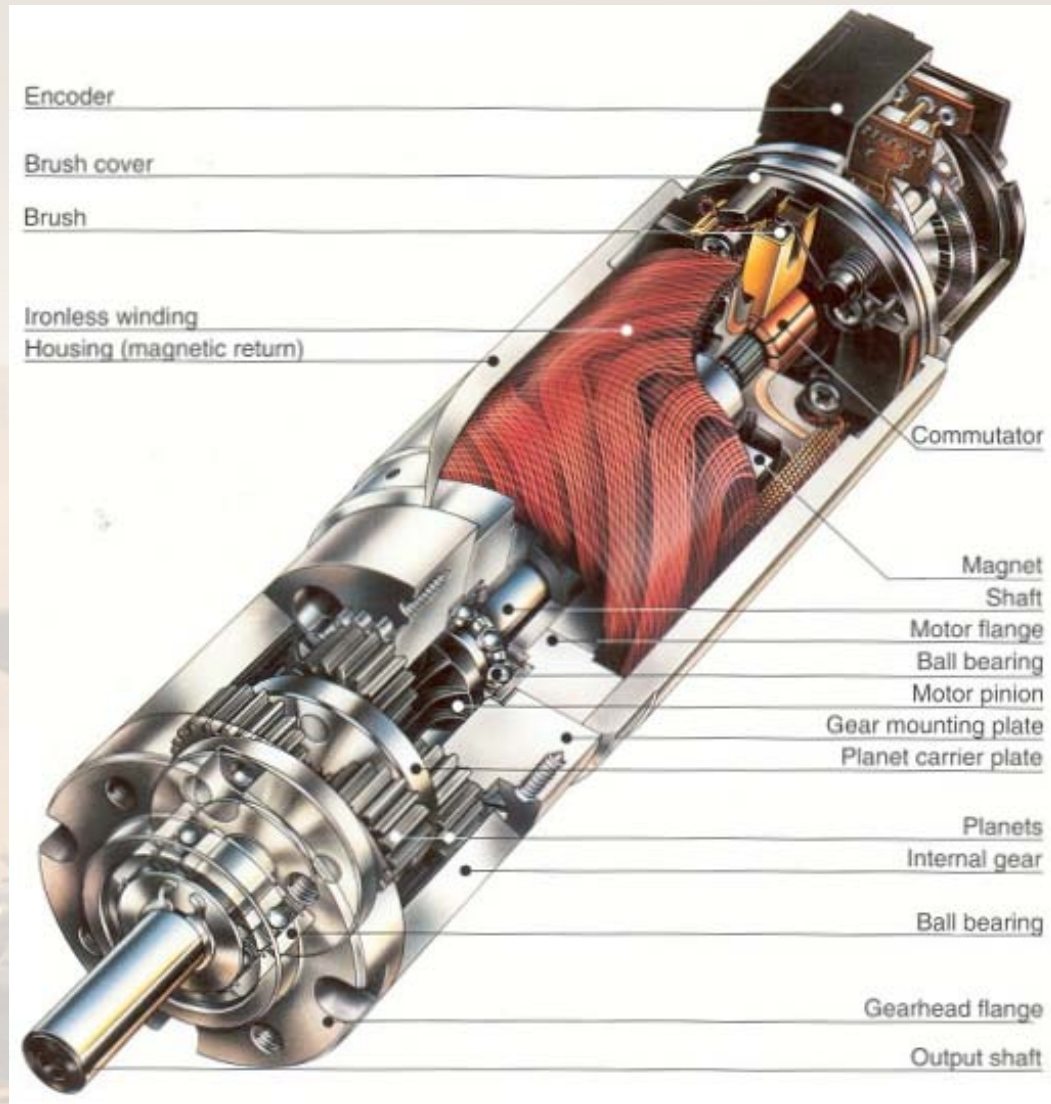


# Stepper Motor Schematic





# Gearhead Motor Cutaway



# Gear Forms

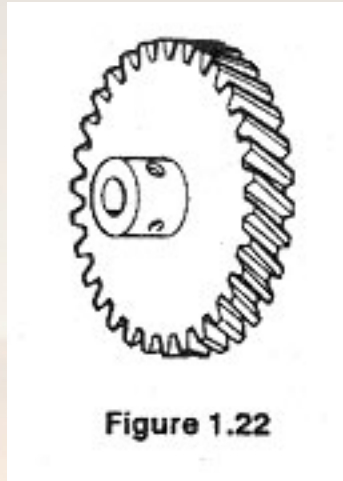


Figure 1.22



Figure 1.41 Typical Right Angle Bevel Gear

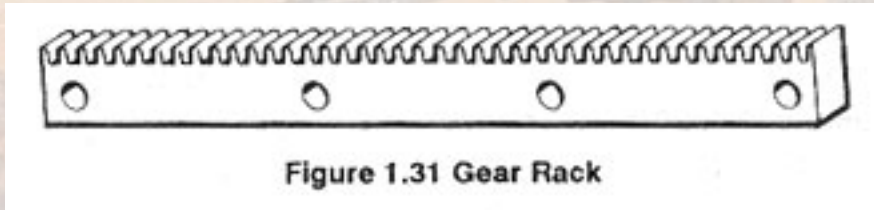


Figure 1.31 Gear Rack



Figure 1.38 Typical Worm Mesh

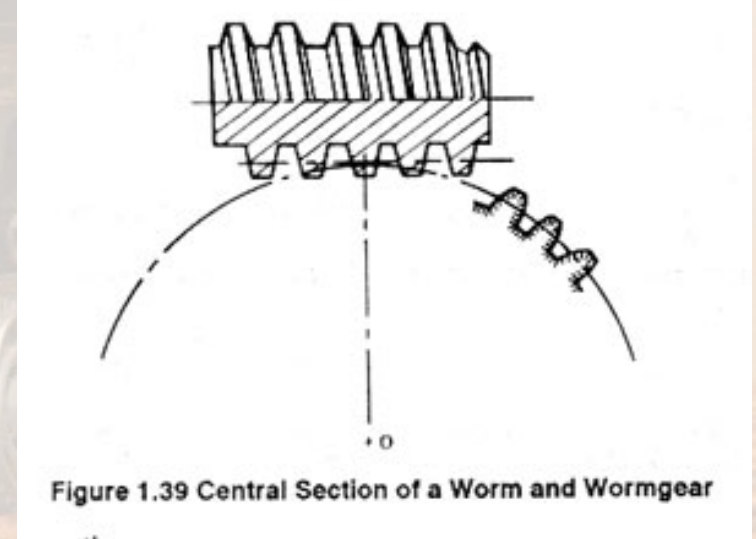


Figure 1.39 Central Section of a Worm and Wormgear



# Gearing Calculations

Gear ratio  $\equiv N$

$$\tau = I\omega \implies I = \frac{\tau}{\omega}$$

$$\tau_{output} = N\eta_{gear}\tau_{input}$$

$$I_{output} = \frac{\tau_{output}}{\omega_{output}}$$

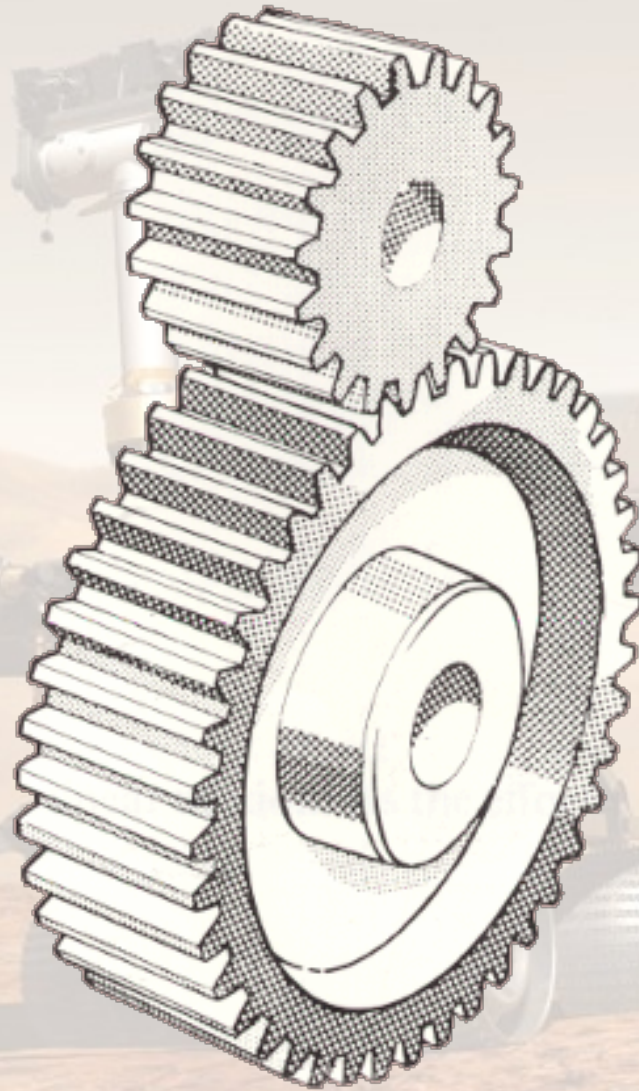
$$\omega_{output} = \frac{\omega_{input}}{N}$$

$$I_{output} = \frac{N\tau_{input}}{\frac{\omega_{input}}{N}}$$

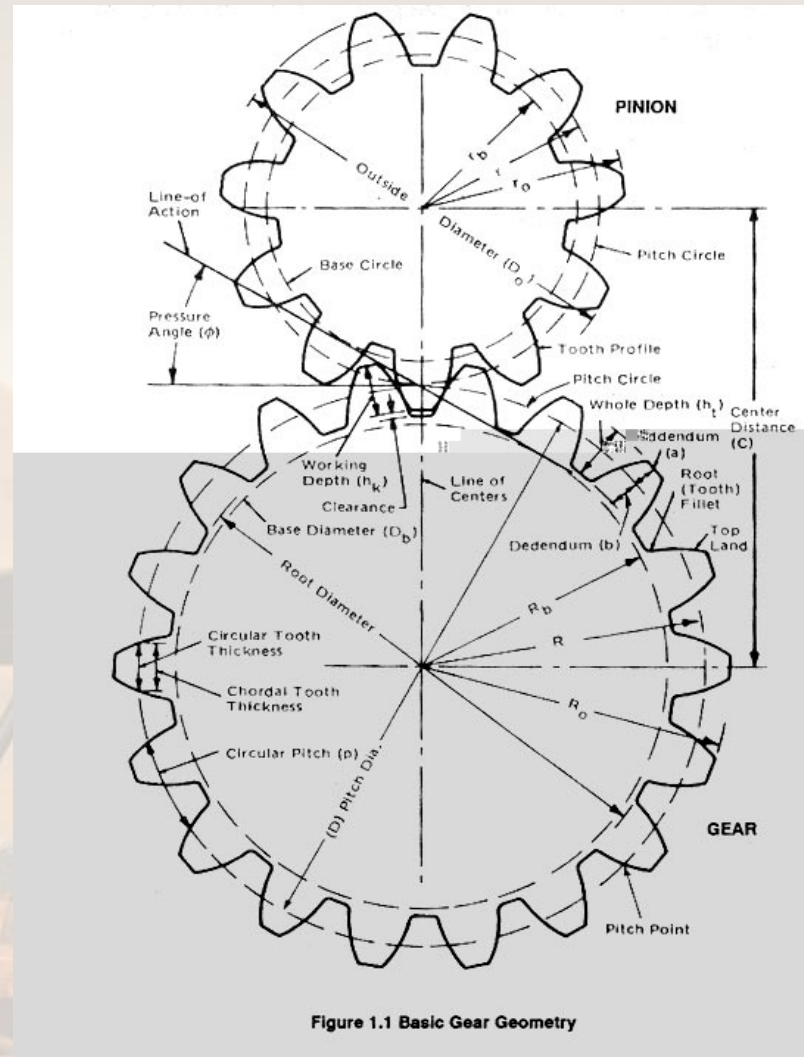
$$I_{output} = N^2 I_{input}$$



# Spur Gears



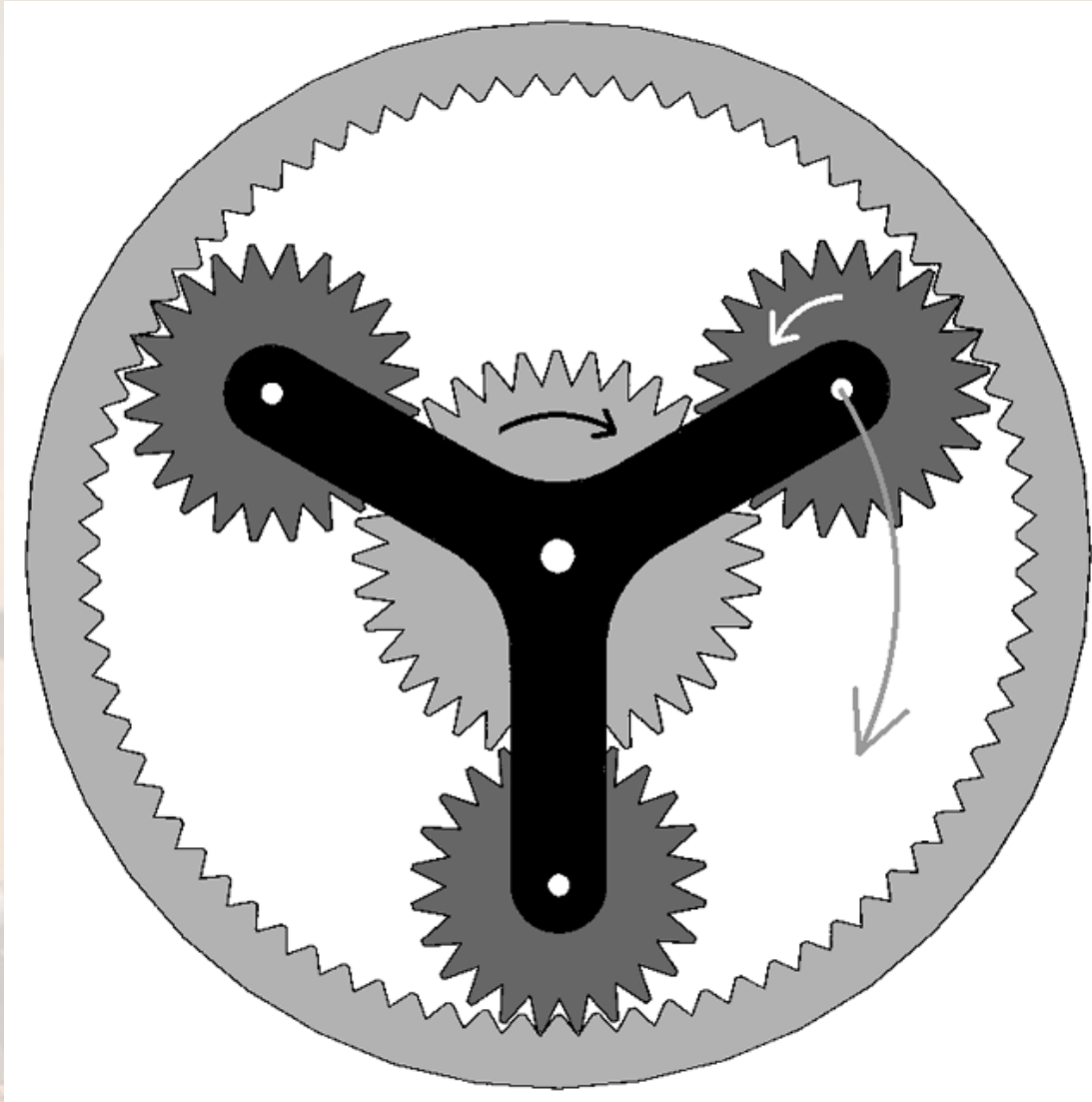
# Spur Gear Parameters



# Helical Gears



# Planetary Gears

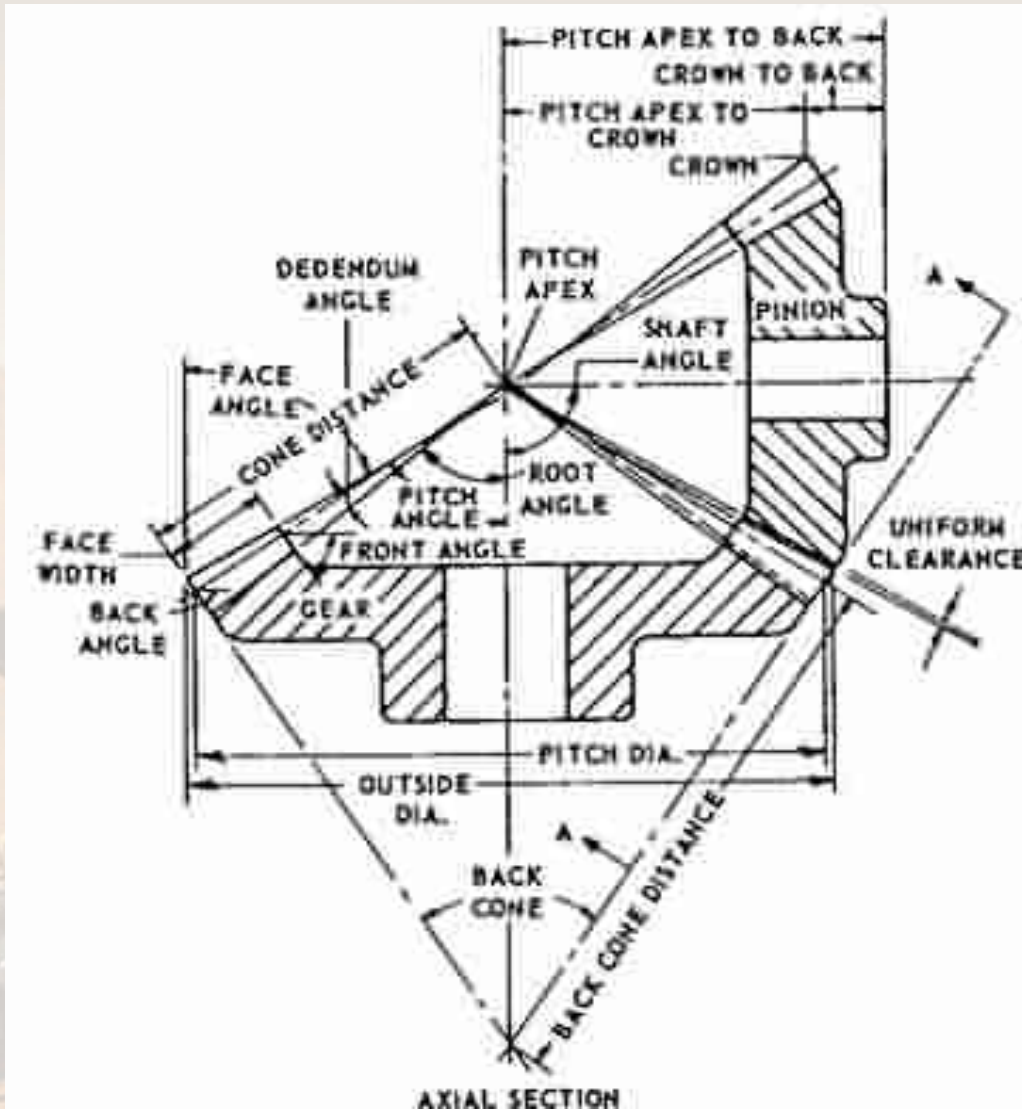


# Bevel Gears

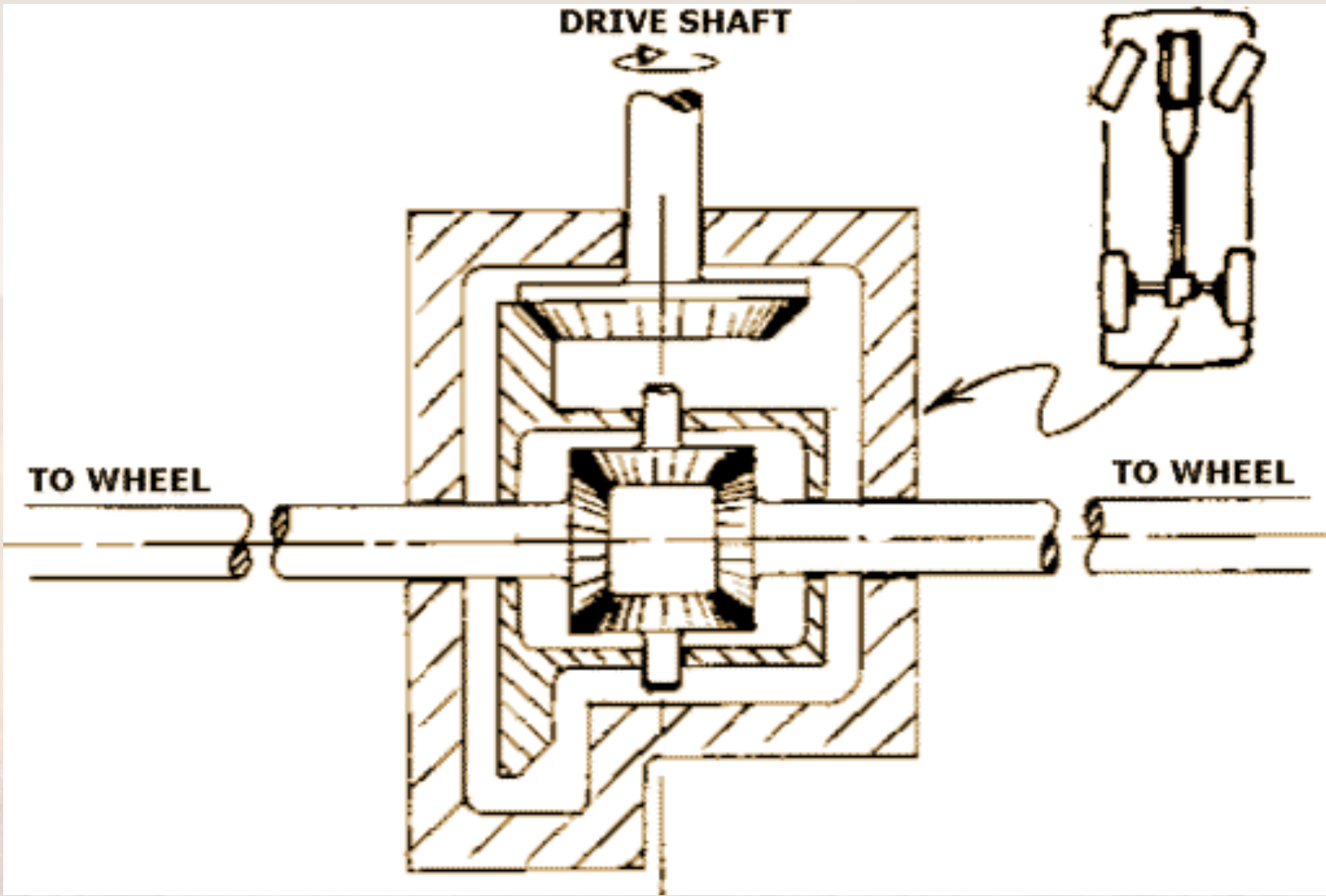




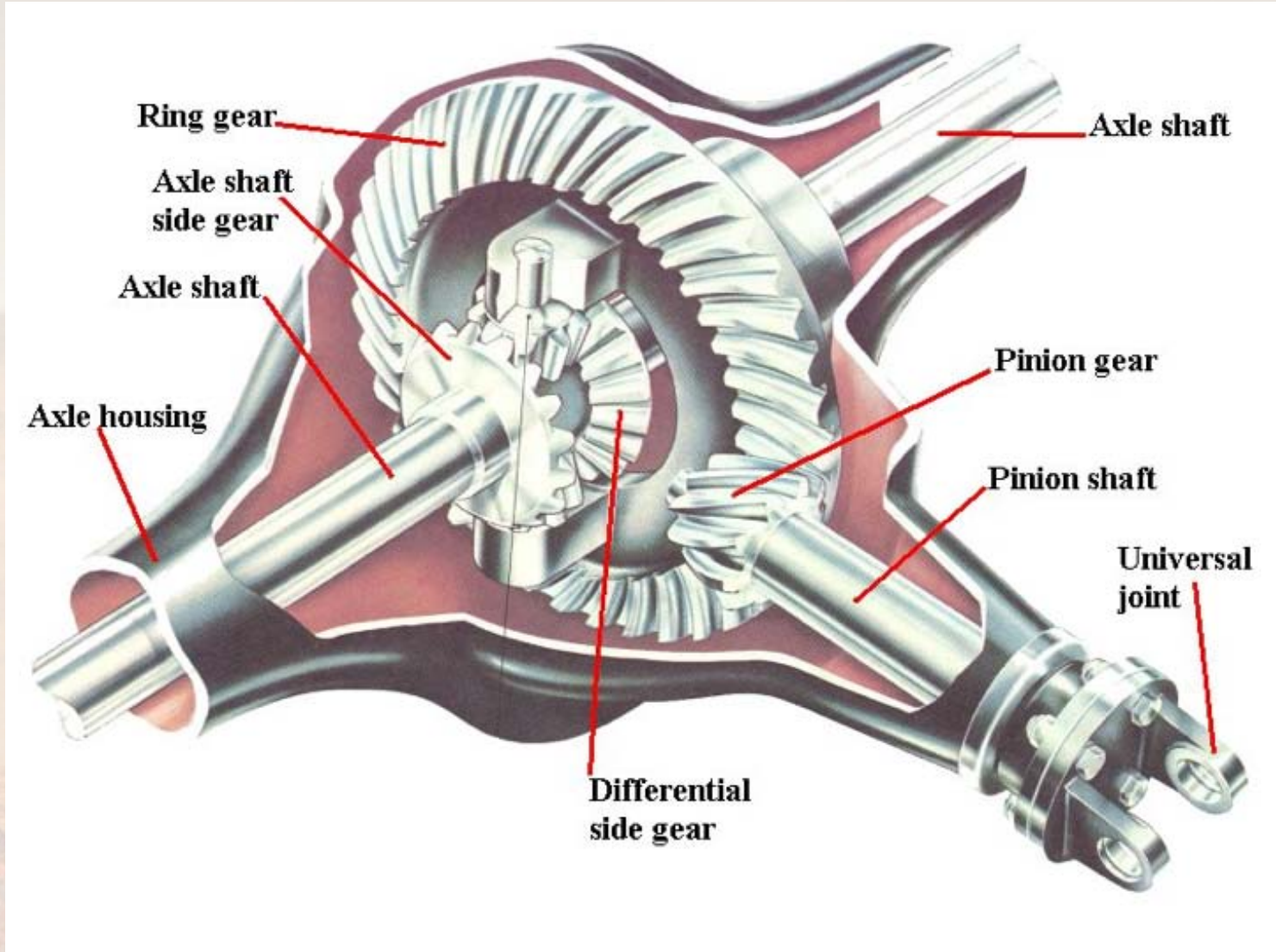
# Bevel Gear Kinematics



# Automotive Differential Schematic



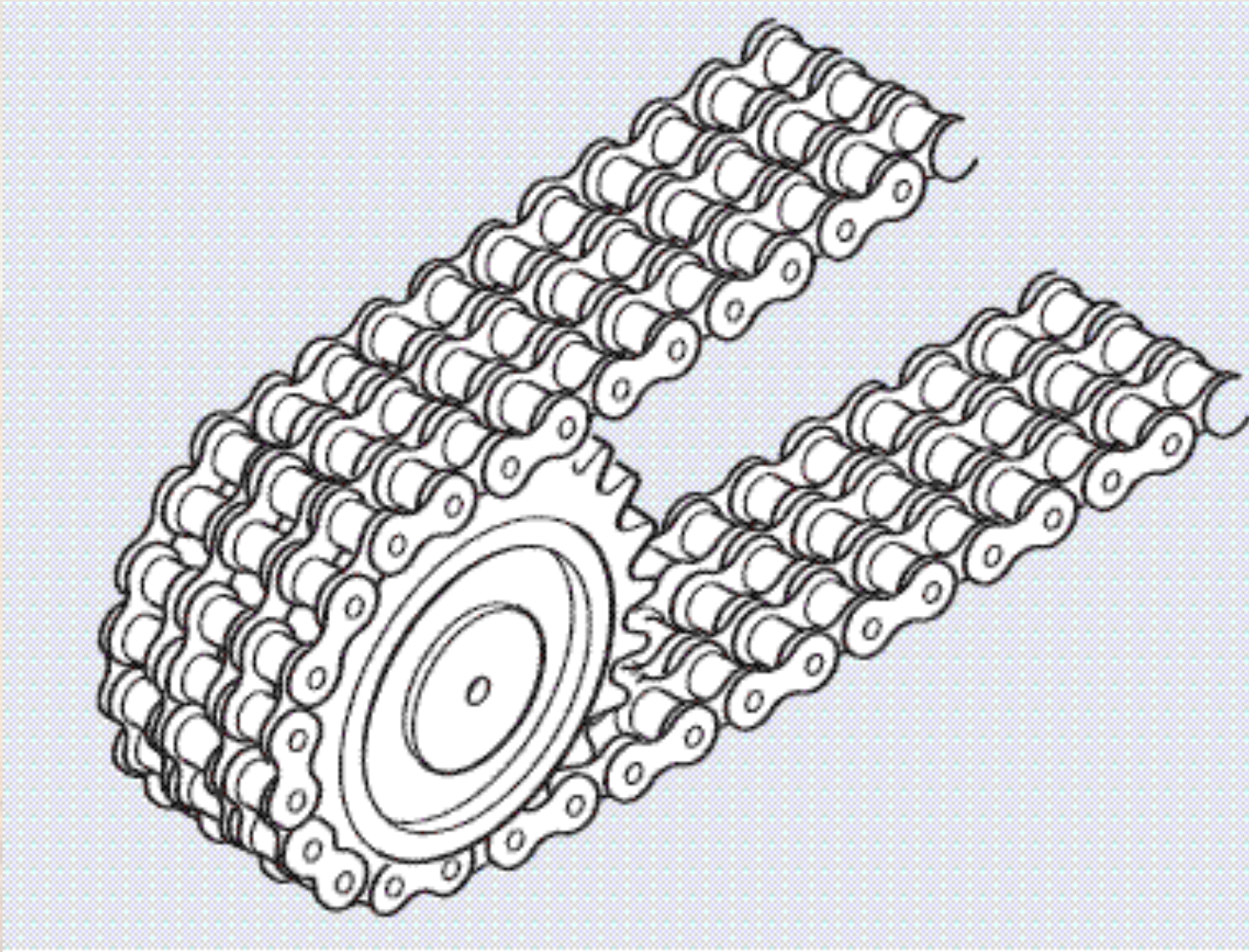
# Automotive Differential (more realistic)



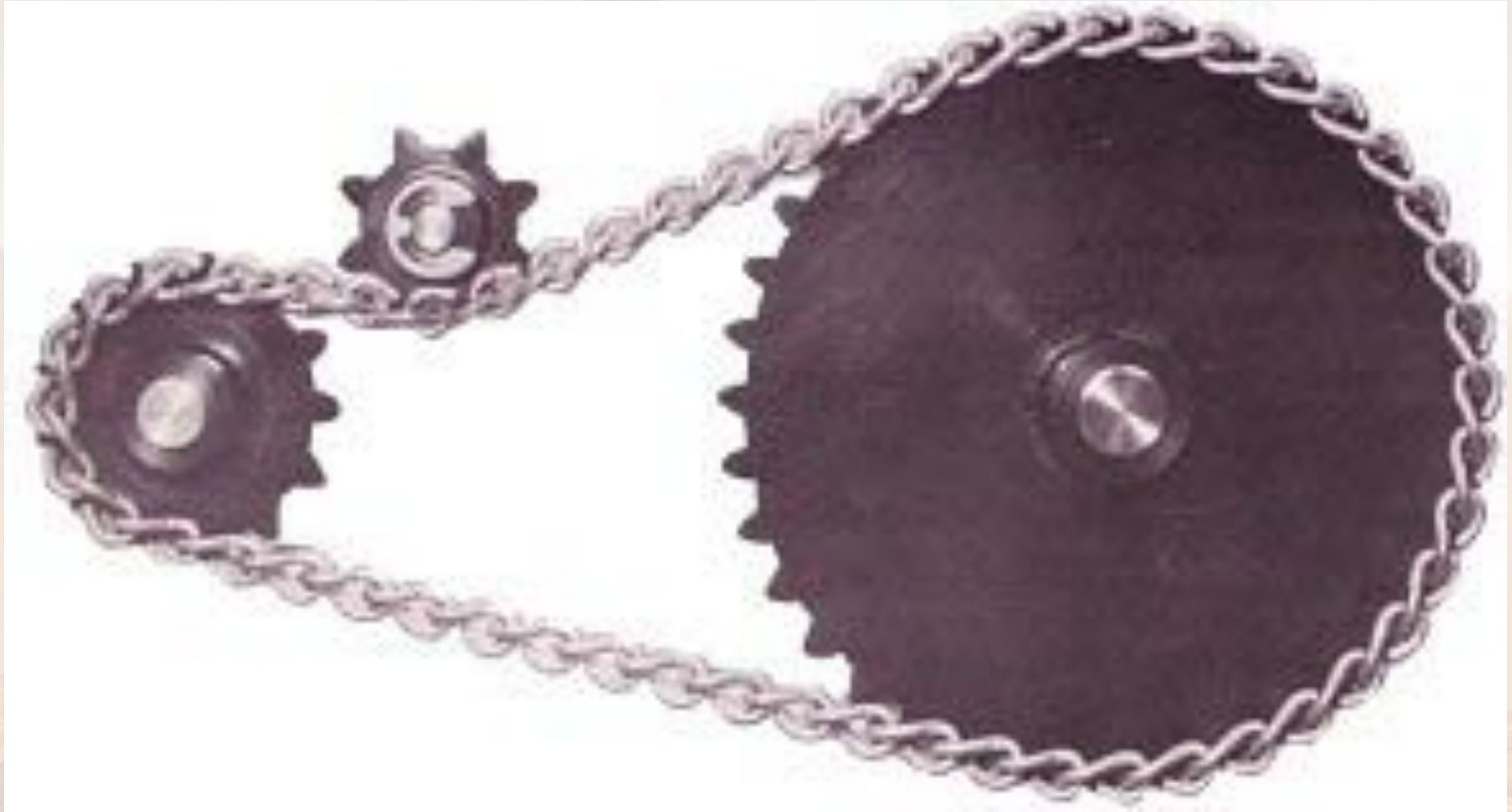
# Worm Gear



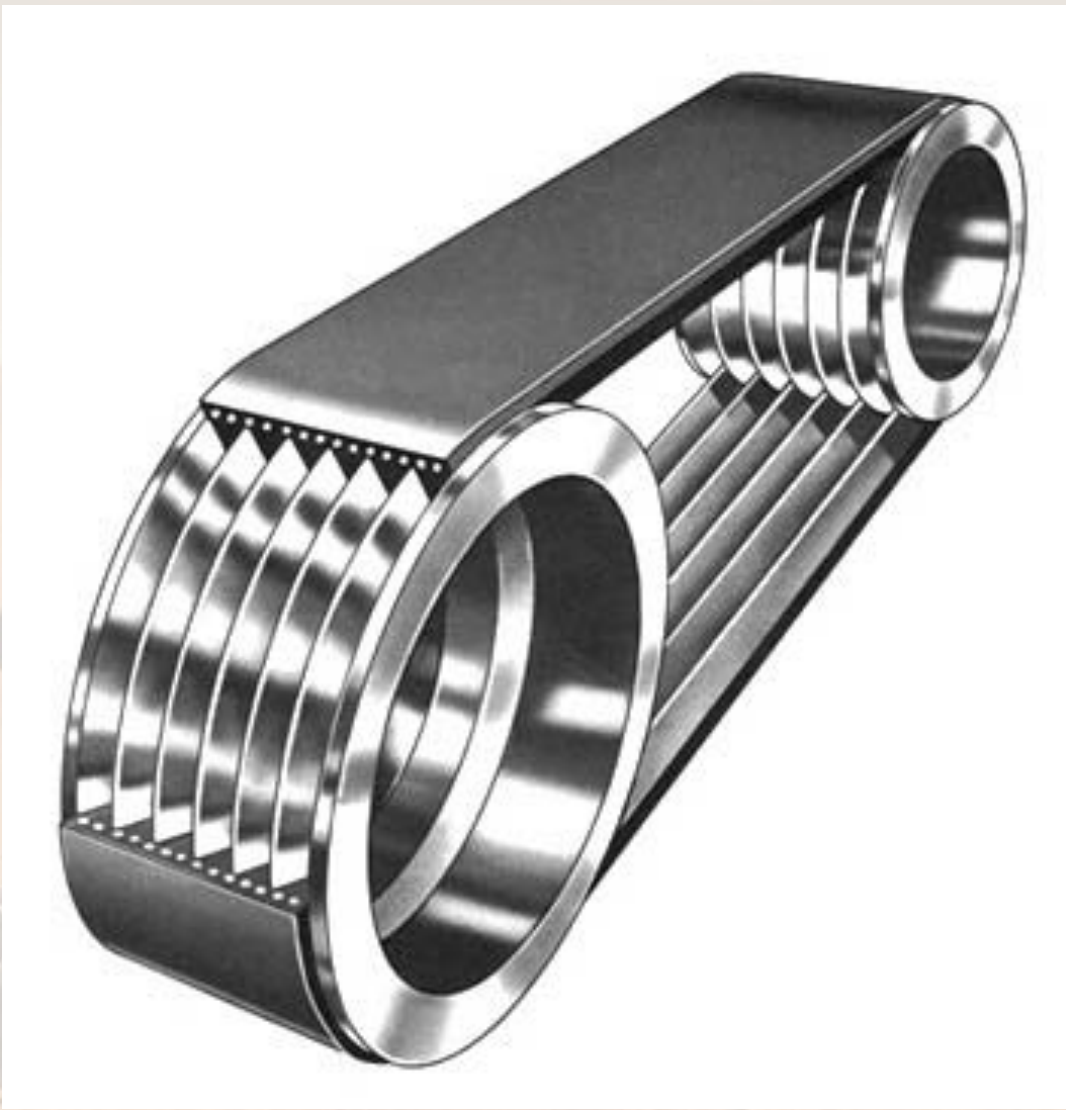
# Chain Drives



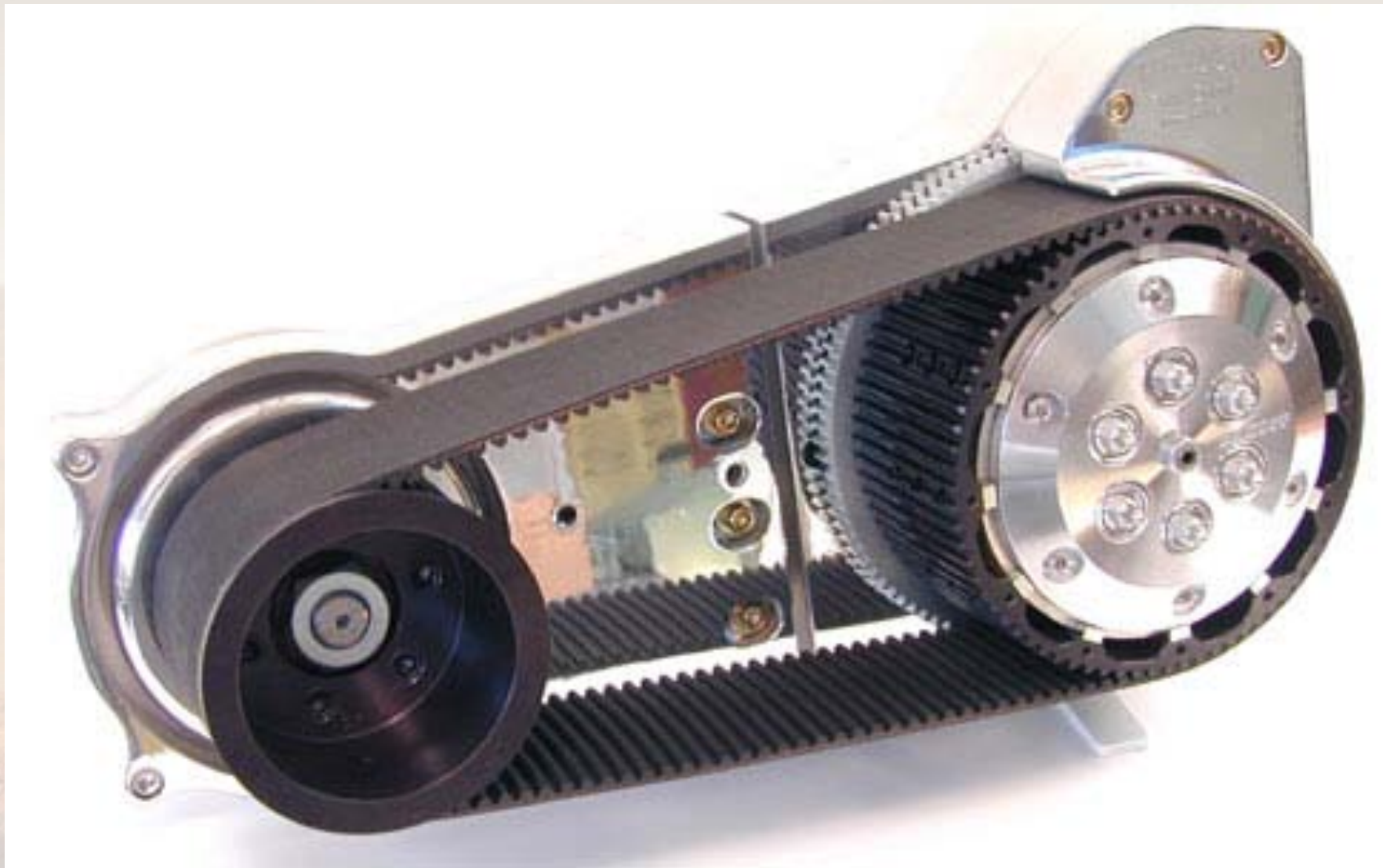
# Chain Drive with Idler



# V-Belt Drive



# Toothed Belt Drive

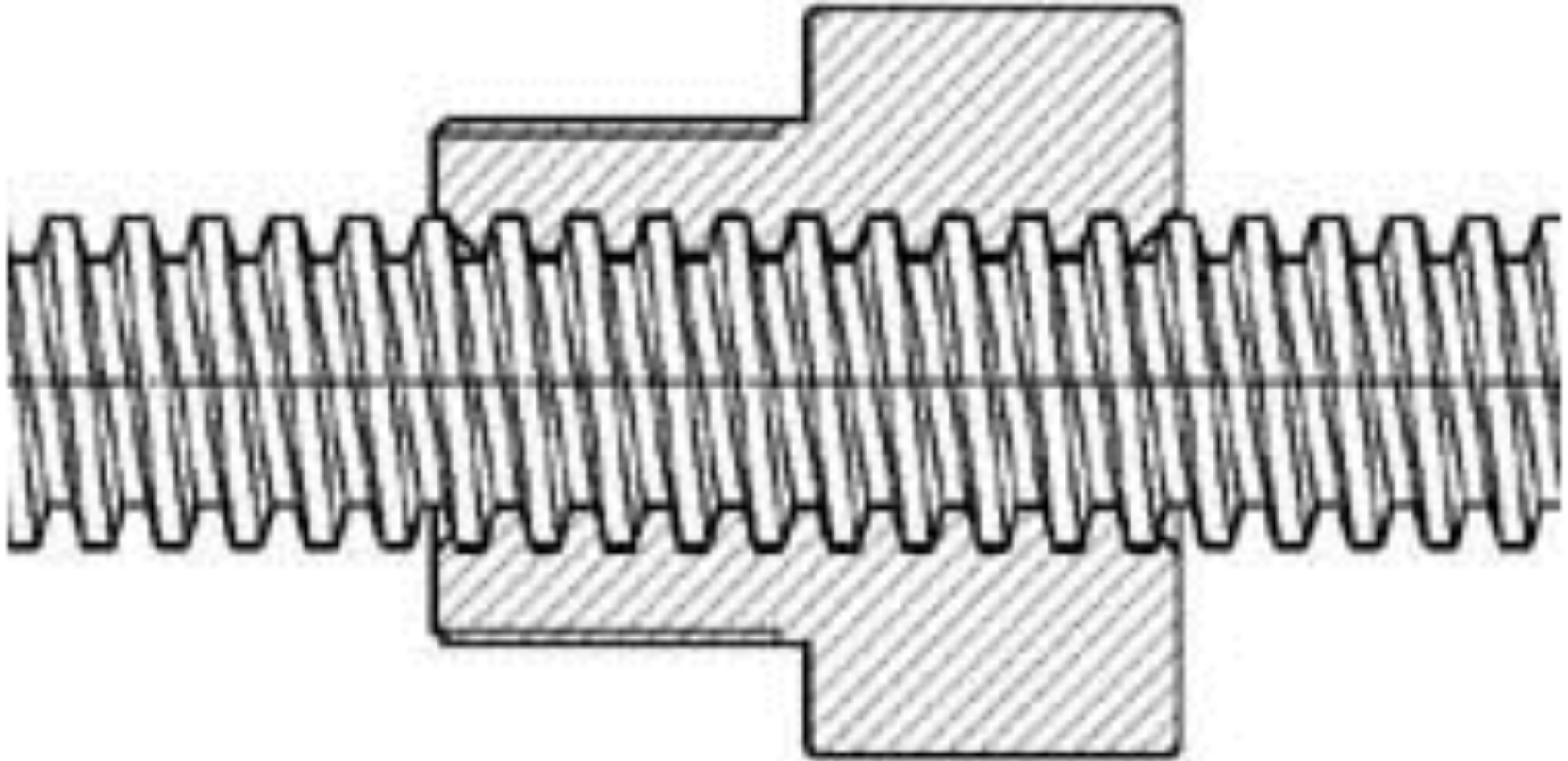




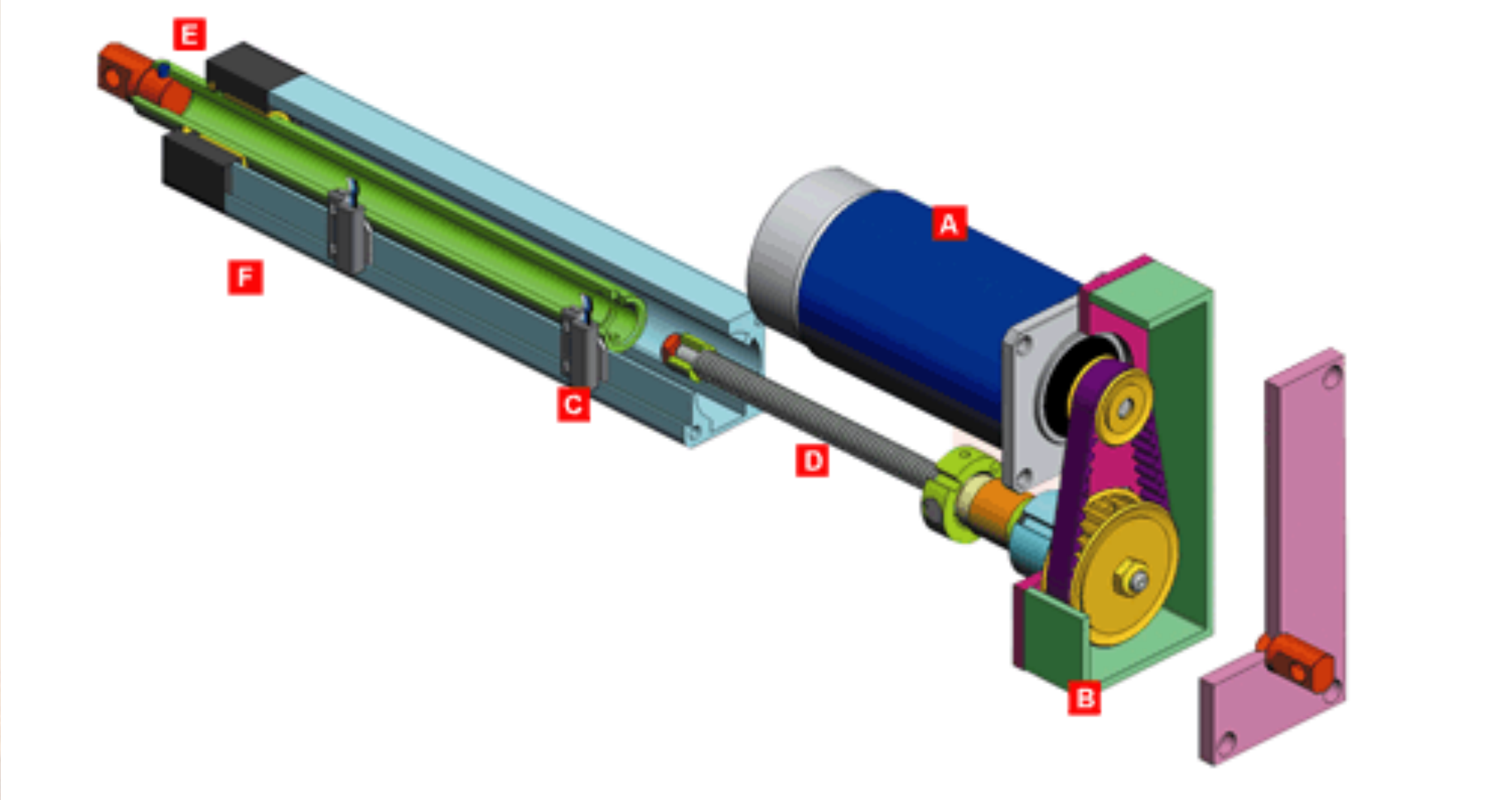
# Rack and Pinion Gears



# Screw Drive Schematic



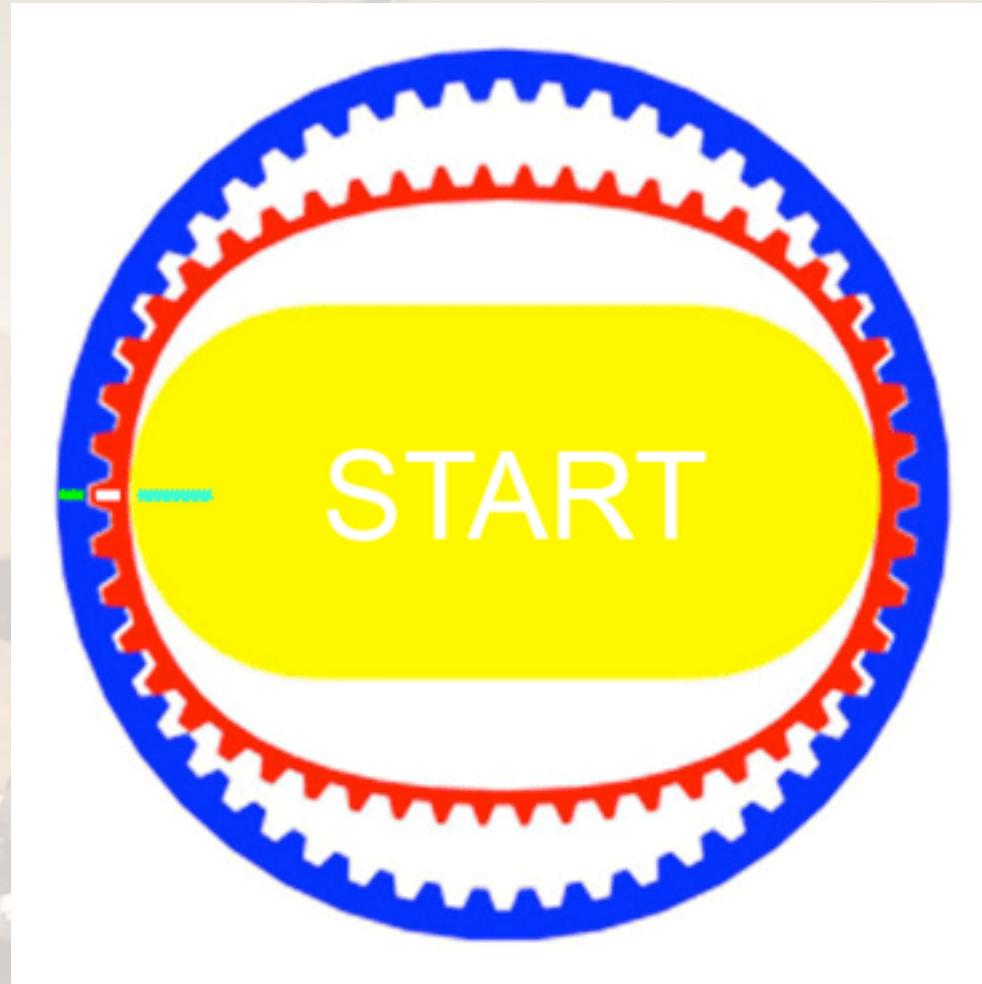
# Linear Actuator Cutaway



# Cup-Style Harmonic Drive

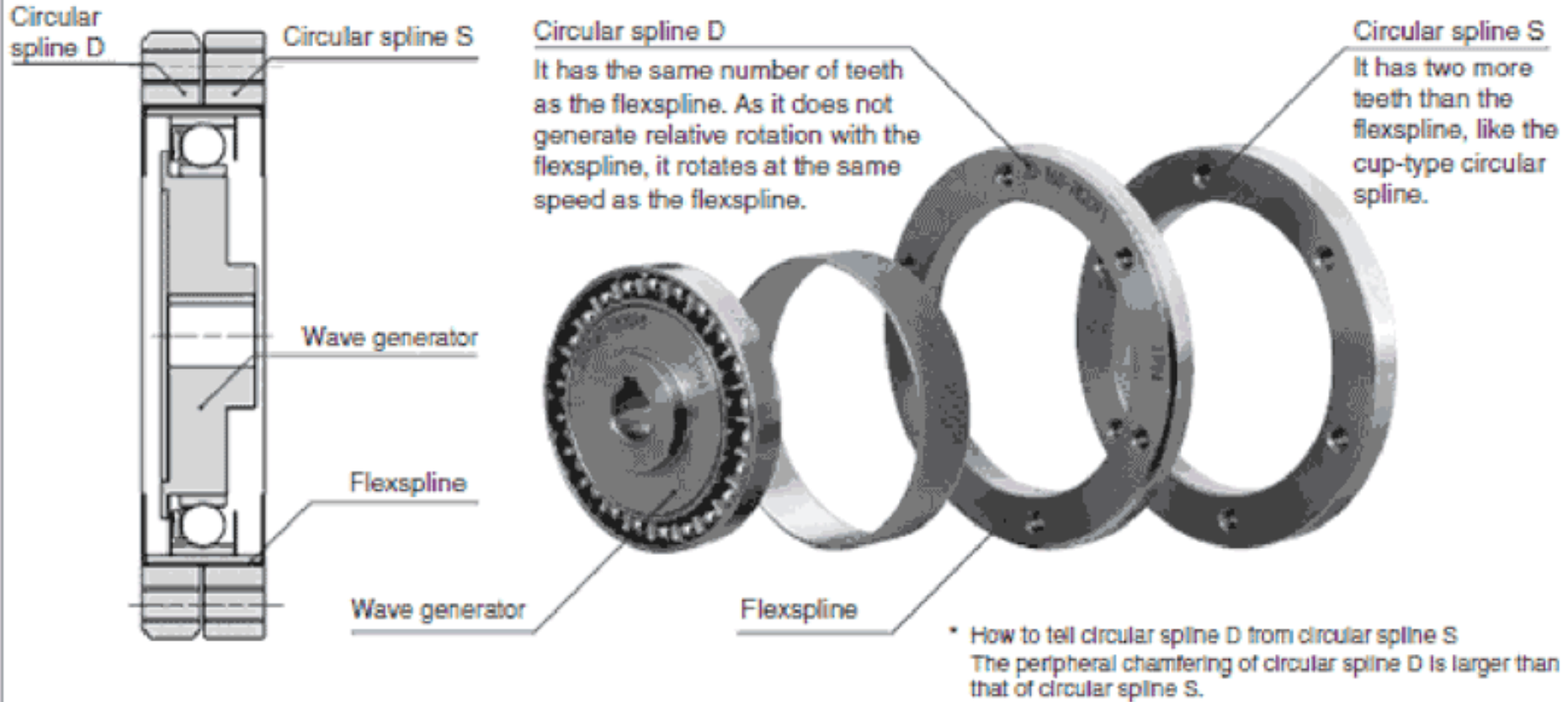


# Operating Principle of Harmonic Drives

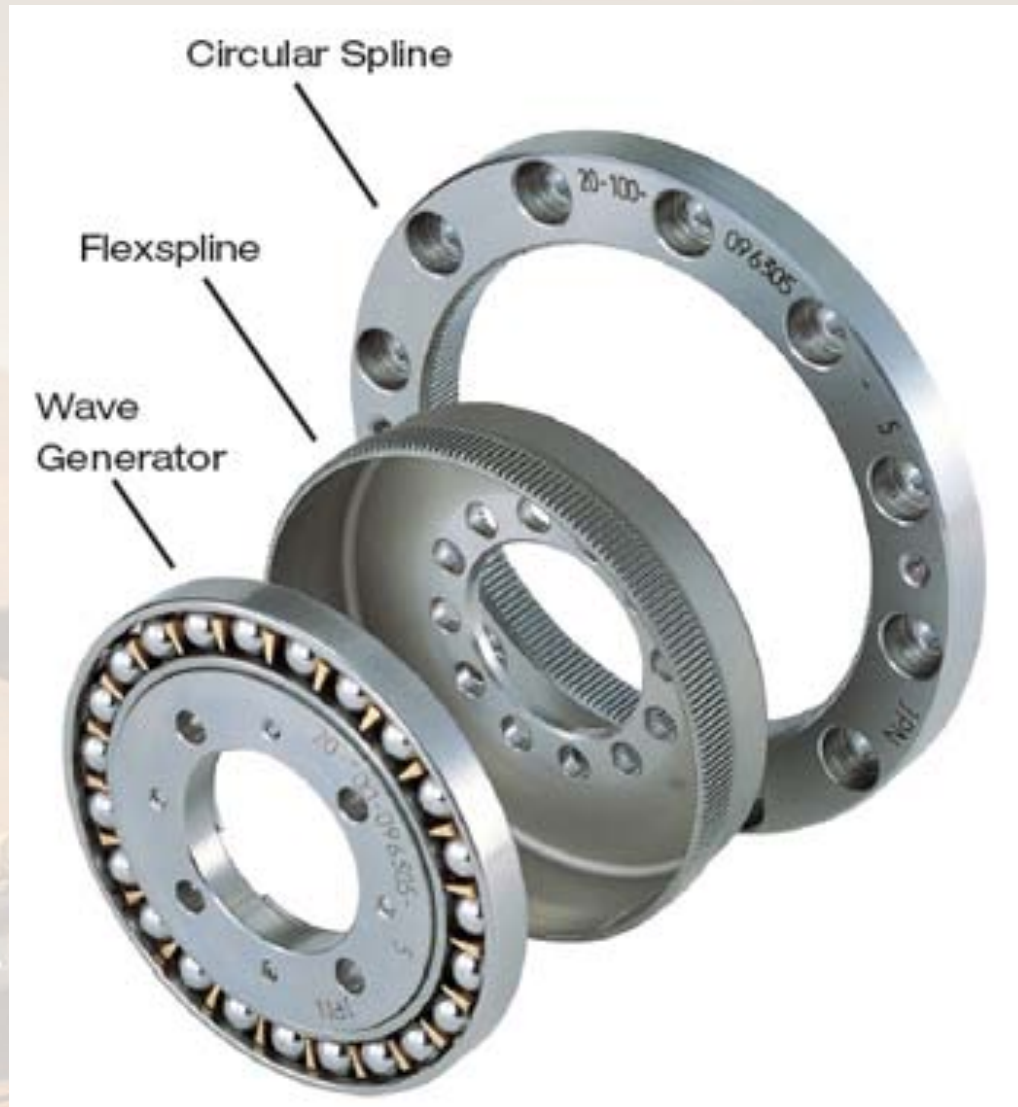


# Pancake Harmonic Drive

## Structure of the FB series component type



# Shallow-Cup Harmonic



# Ball Bearings

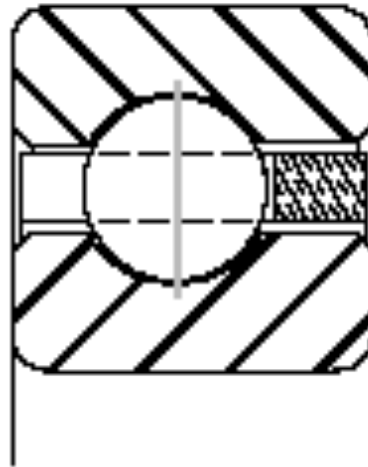




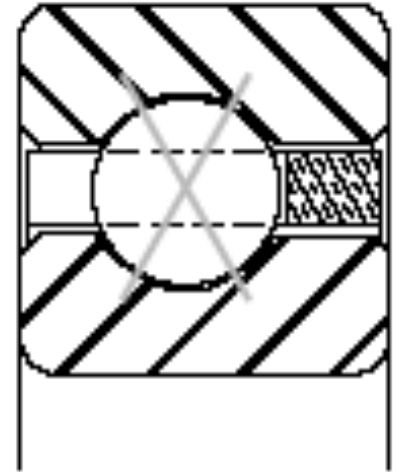
# Types of Bearings



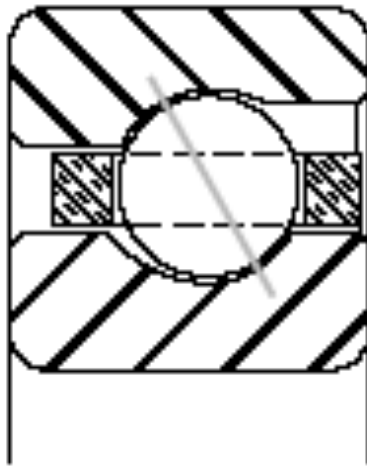
**Type C—Radial Contact**



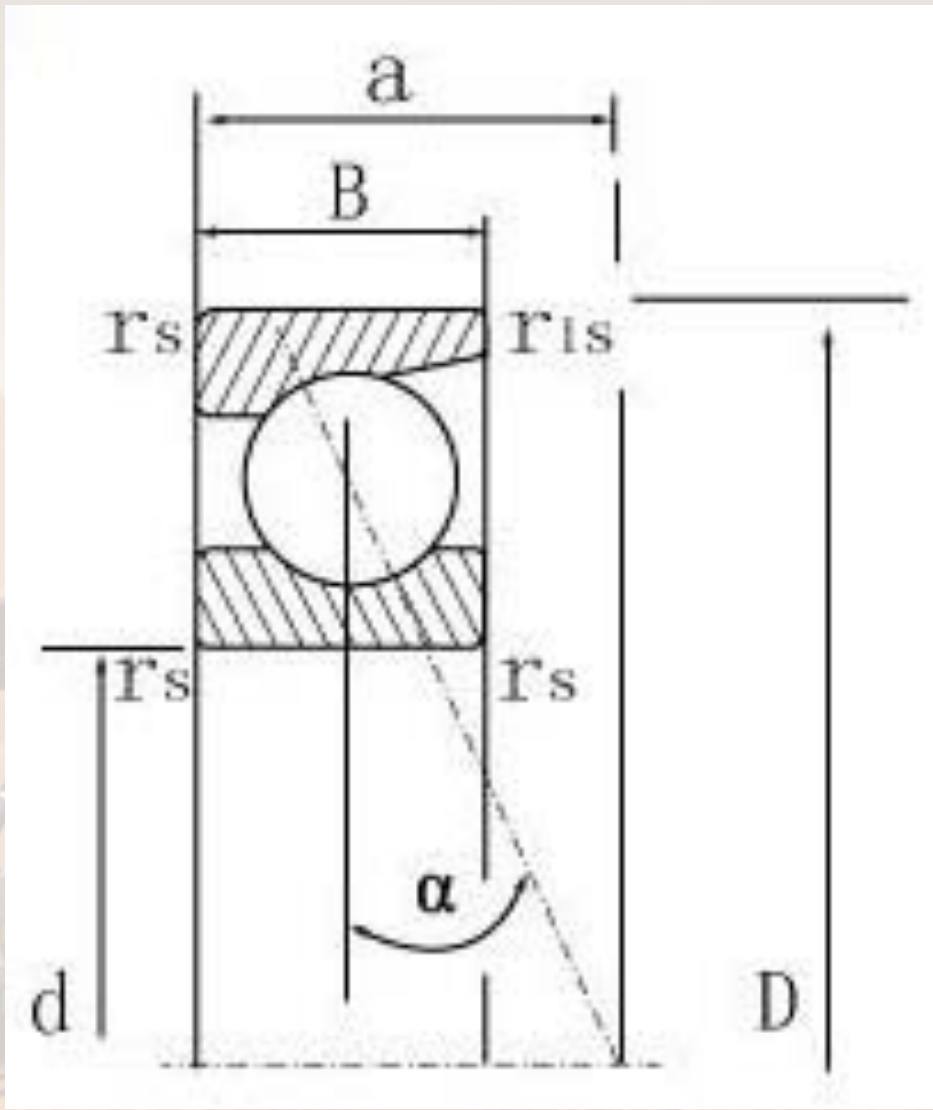
**Type X—Four Point Contact**



**Type A—Angular Contact**



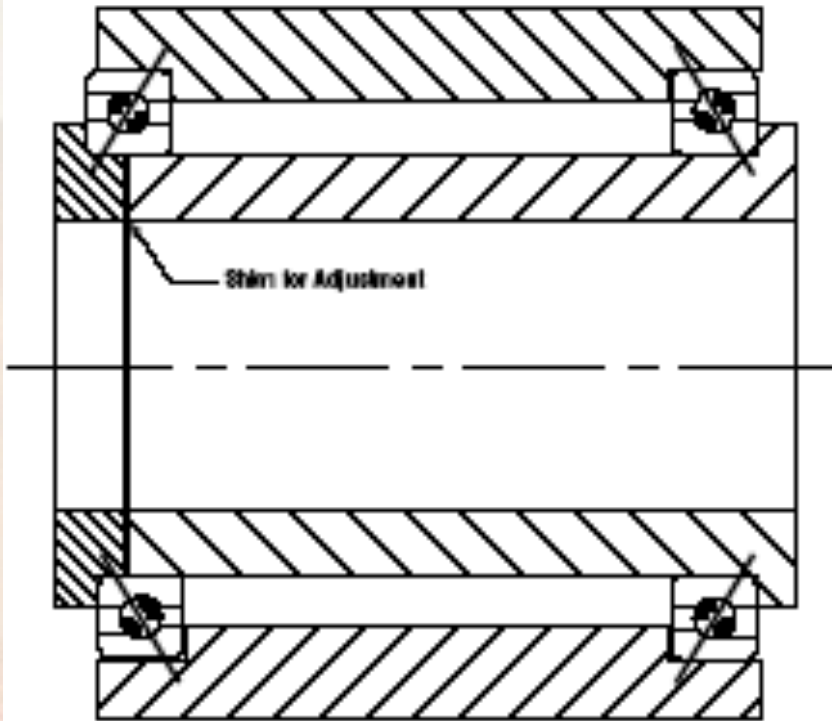
# Angular Contact Bearing



# Ideal Bearing Applications

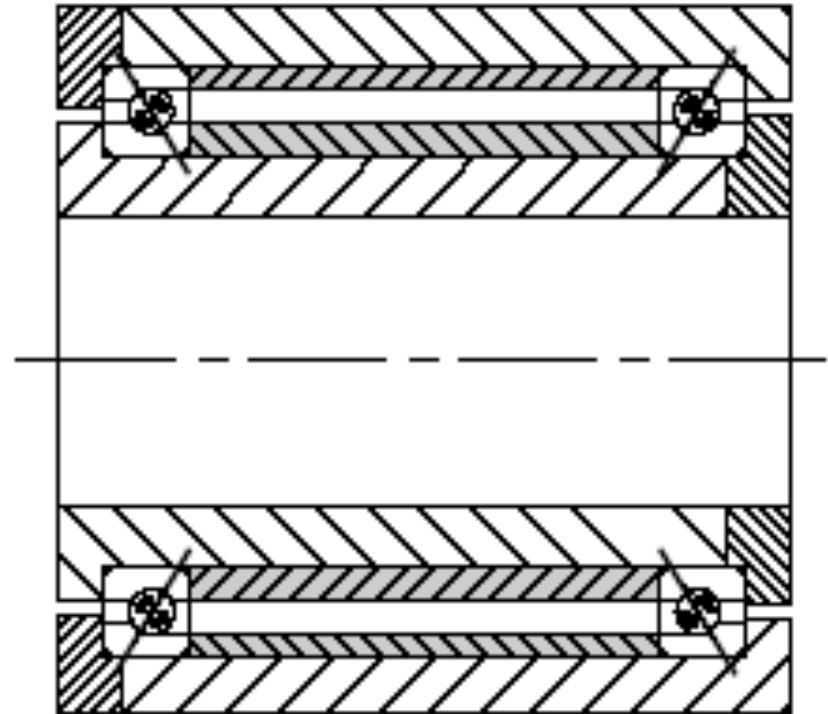
## Back-to-back Mounting

Figure 20

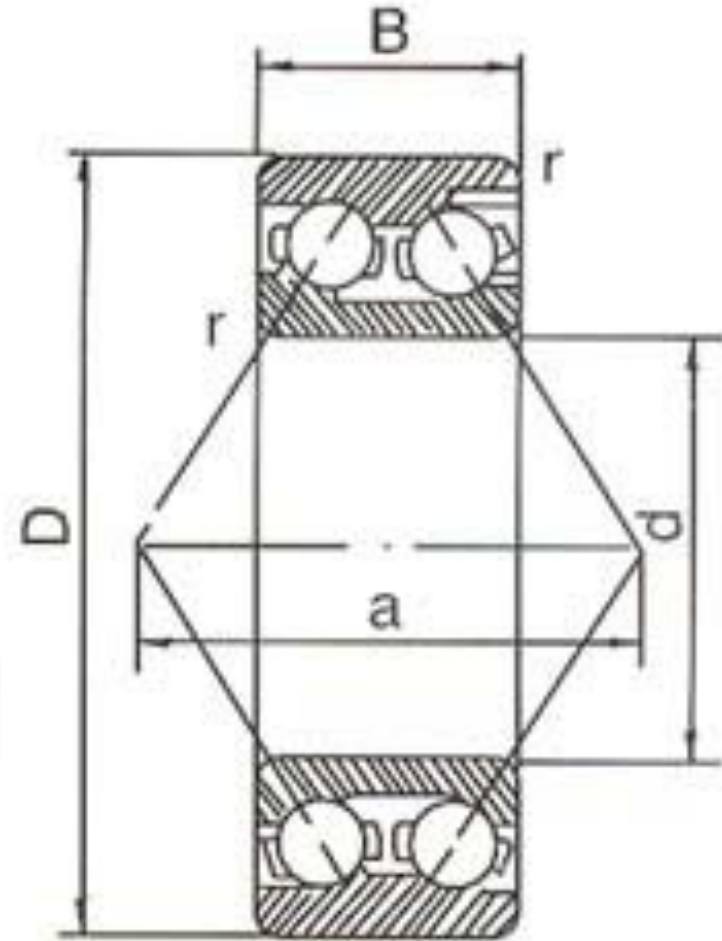
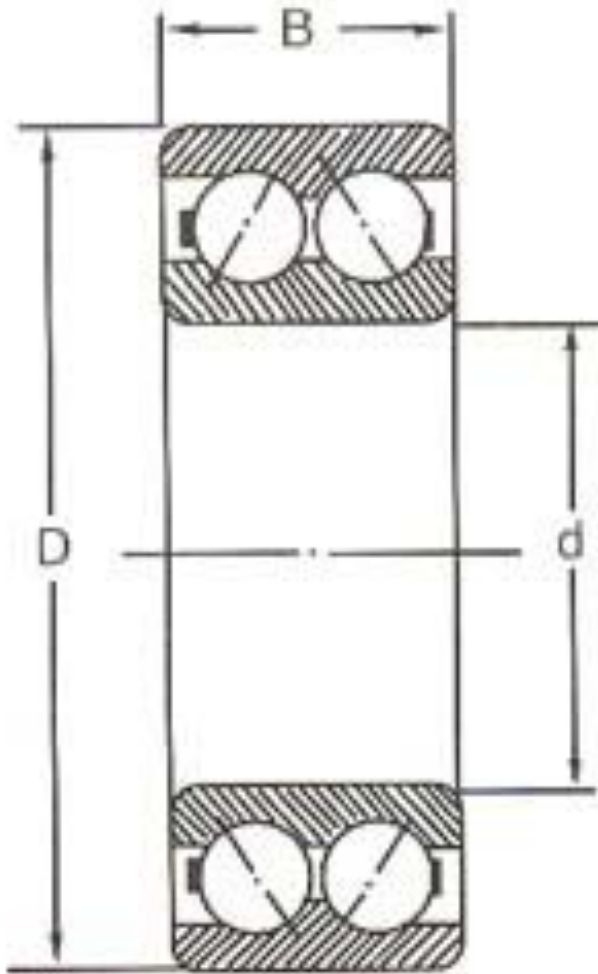


## Face-to-face Mounting

Figure 21



# Dual-Row Angular Contact Bearing



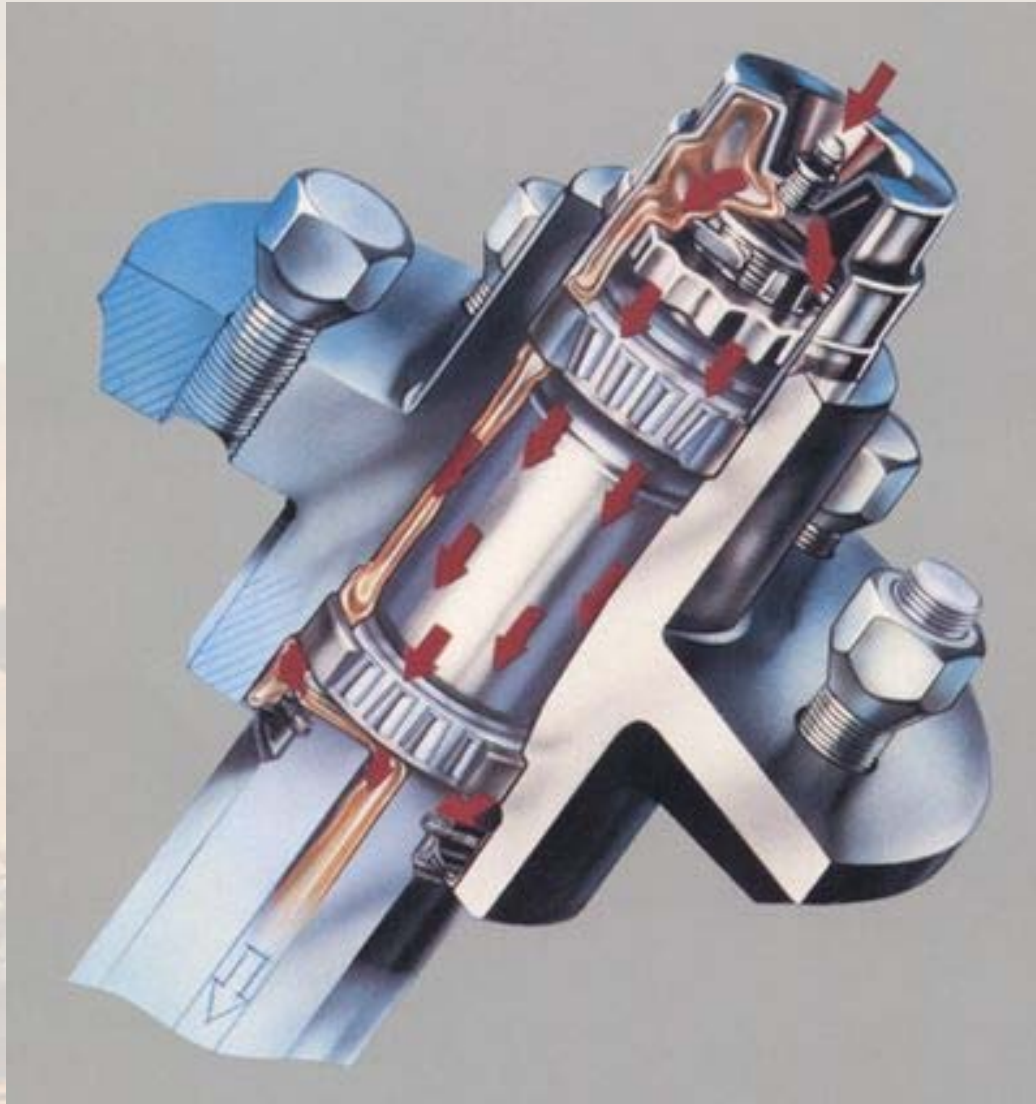
# Thrust Bearing



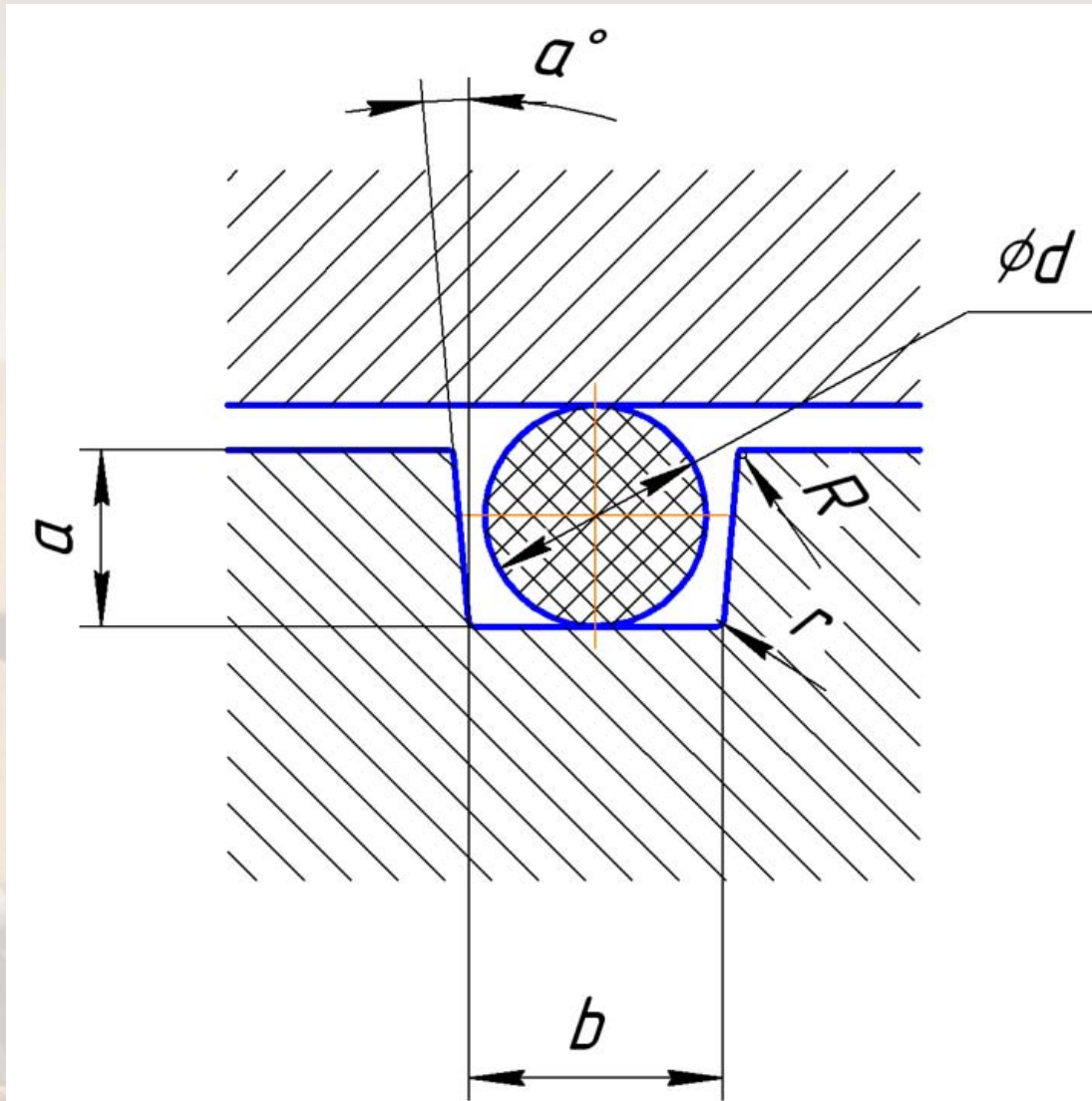
# Tapered Roller Bearings



# Wheel Hub Cutaway



# O-Ring and Groove



































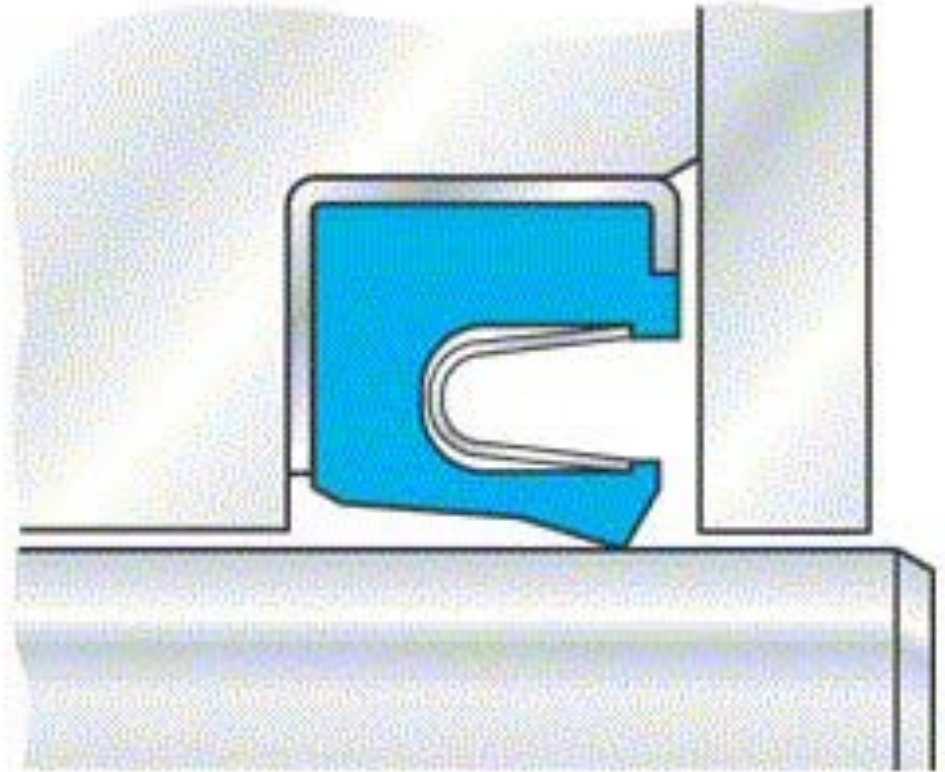
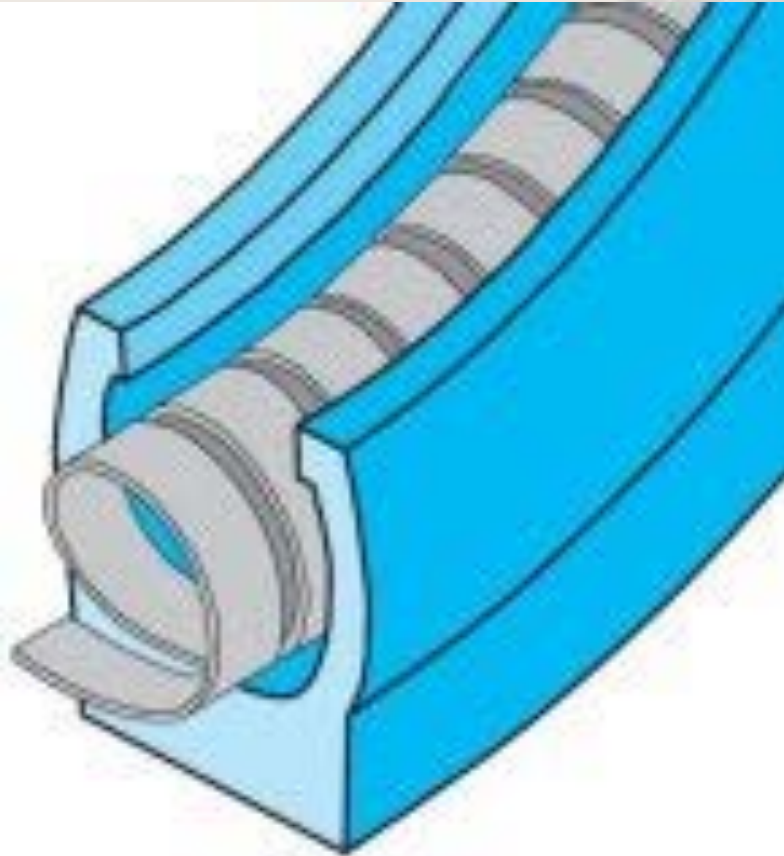
# Lip Seals



## LIP SEALS (LS)

 LS1	 LS1-ng	 LS2	 LS3	 LS4	 LS5	 LS6	 LS7	 LS8	 LS9
 LS10	 LS11	 LS12	 LS13	 LS14	 LS15	 LS16	 LS17	 LS18	 LS19
 LS20	 LS21	 LS22	 LS23	 LS24	 LS25	 LS0	 LS26	 LS27	 LS28

# Spring Energized Seals



# Labyrinth Seals

