Training III

Force Generation and Transmission

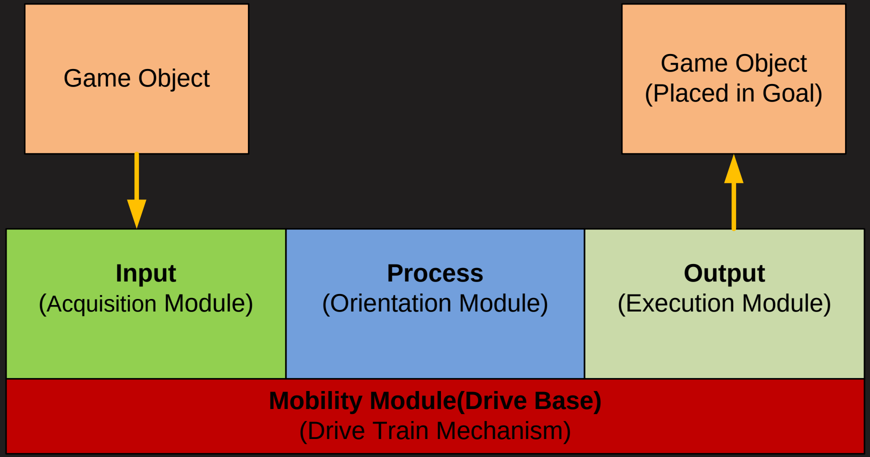
Force Generation and Transmission Objectives

- Understand Energy Conversion to do Work on Robots
- Understand mechanical advantage through gears and pistons
- Understand mechanism energy calculations
- Understand motor electrical characteristics
- Understand motor / gear selection

What is a FIRST Robot

A FIRST Robot is an programmable electro-mechanical machine that performs tasks through end effectors. It performs these tasks in either an autonomous or semi-autonomous mode.

FIRST Robot Block Diagram



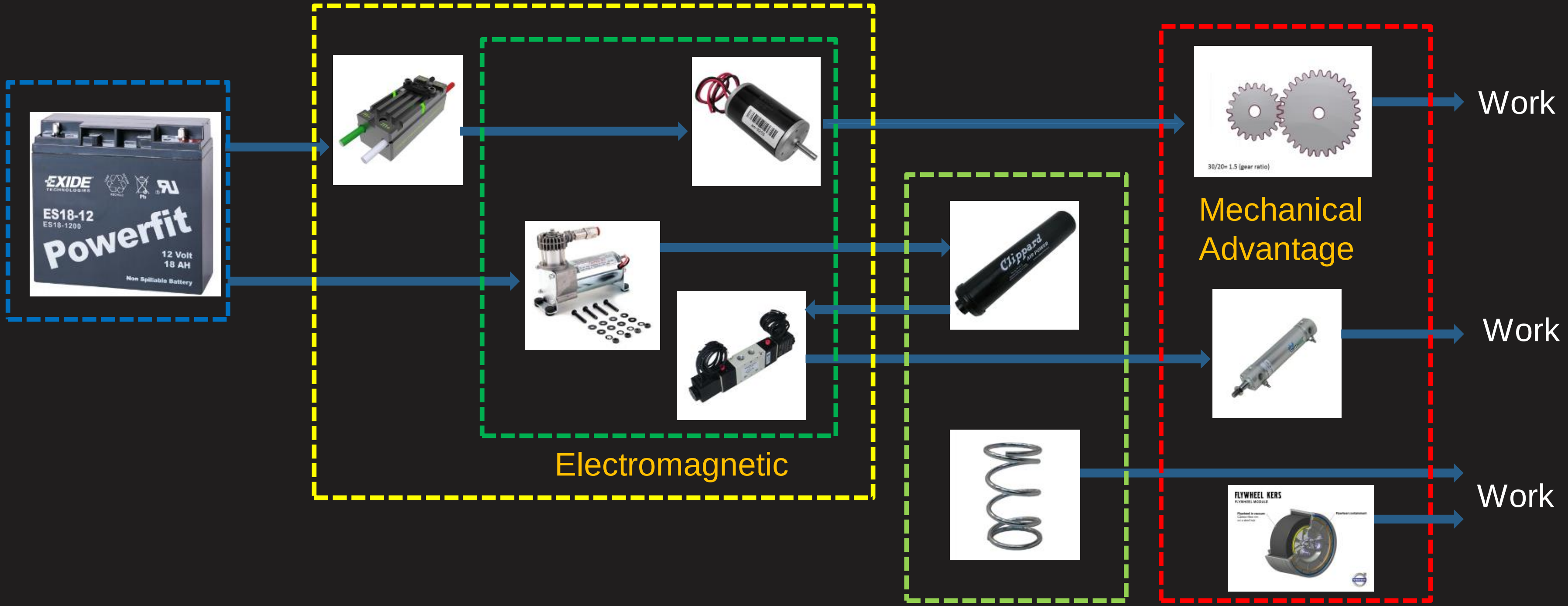
Energy Conversion to Do Work

Chemical Energy

Electrical Energy

Mechanical Potential Energy

Mechanical Kinetic Energy



Mechanical Energy (Linear)

Mechanical Energy is the energy acquired by objects upon which work is done

Mechanical Energy has two forms: Potential Energy and Kinetic Energy

E_{mech} = PE + KE;

PE → KE
Motion

Kinetic Energy(KE) – Energy of motion

KE = ½ x m x v^2;

Potential Energy(PE) – Stored energy of position

Gravitational:

PE = m x g x h

Elastic – energy stored in elastic materials – Spring, surgical tubing:

PE = ½ x K x x^2; where K – spring constant

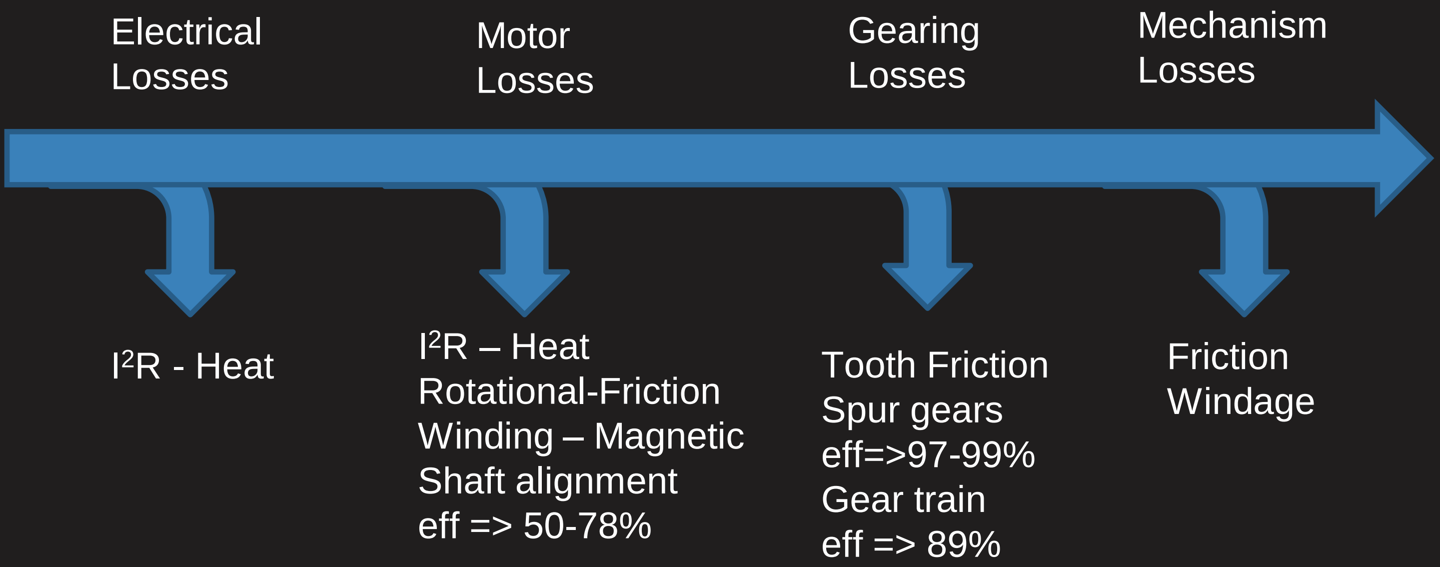
Also - Compressed Air(Elastic):

PE = P_i x V_i x ln(P_f / P_i)

Conservation of Energy

Conservation of energy:
“Energy can neither be created of destroyed; rather, it transforms from one form to another”
Wikipedia

Energy OUT NOT EQUAL to Energy IN – Why?



Energy ⟷ Work

"Work is the Energy transferred by a Force"

↑ ↓

"Energy is the ability to do work"

Wickipedia

Joule is a unit of energy and work

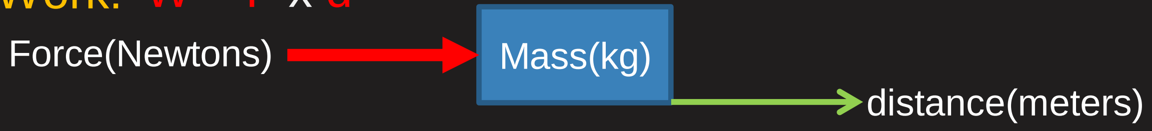
Work

Work shifts energy from one system to another

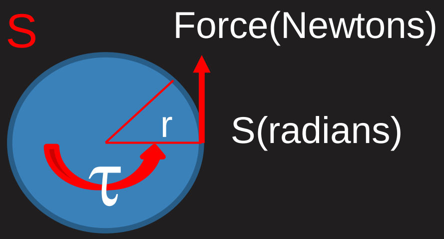
Work(Joules) = Force(Newtons) x distance(meters)

Note: $J = Nm = (kg \times m / s^2) \times m = kg \times m^2 / s^2$

Linear Work: $W = F \times d$



Rotational Work: $W = F \times r \times S$



Torque(Twisting Force): $\tau = F \times r$

Power

Power is the rate at which work is done

Power(watts) = Work(Nm) / Time(seconds)

P = F x d / s - Note: 1 watt = 1 Joule/sec

P = F x v (linear)

P = τ x ω (rotational)

Horsepower:
Metric 1Hp = 736watts
Electrical Hp = 746watts
Mechanical Hp = 745.7watts

1 ft-lbf / sec = 192 in-lbf / sec= 1.356 watts

Force

Force is the property of imparting acceleration to particles or objects

(It is the push or pull on an object as a result of its interation with another object)

Newton's Second Law of Motion:

Force on an object produces an acceleration (change in velocity)

F(Newtons) = mass(kg) x acceleration(meters/second^2)

$1N = kg \cdot m \cdot s^{-2}$

Kg is the standard for mass

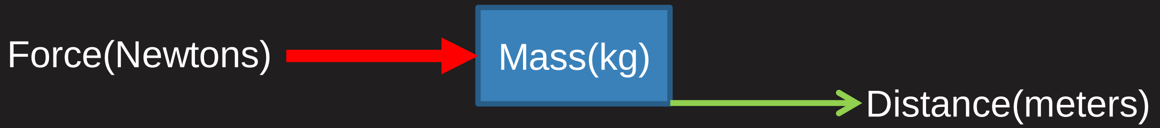
1kg = mass of 1 liter of water

Acceleration = $(V_f – V_i) / (t_f – t_i)$

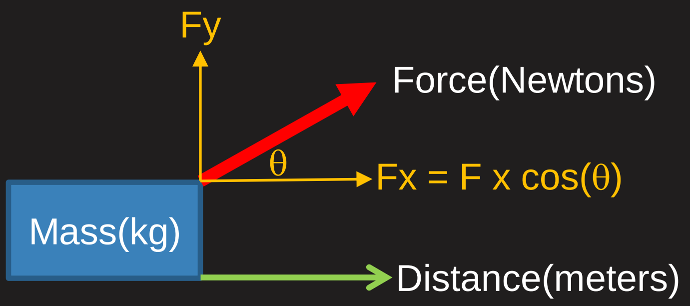
Linear Force

Force is a vector; It has Magnitude and Direction

Linear Work: $W = F \times d$



Linear Work: $W = F \times \cos(\theta) \times d$



Linear Force on Incline (Traction)

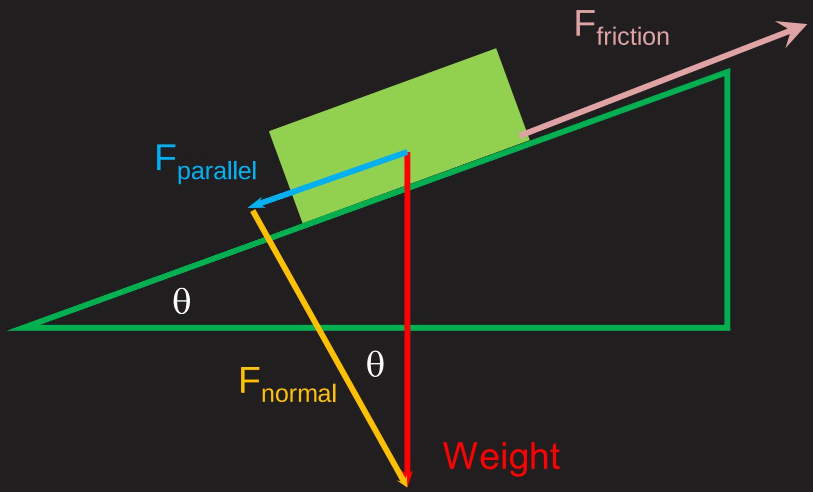
- $F_{friction} = \mu \times F_{normal}$ (Experimentally determine μ)

- $F_{normal} = Weight \times \cos(\theta)$
- $F_{parallel} = Weight \times \sin(\theta)$

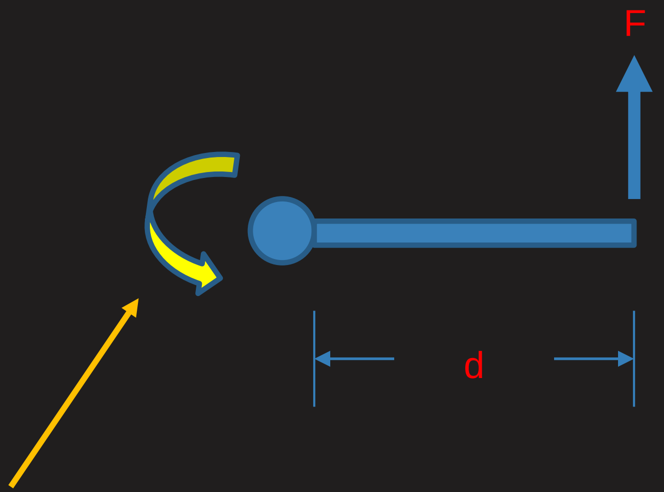
- When $F_{parallel} = F_{friction}$; no slip

$Weight * \sin(\theta) = \mu * Weight * \cos(\theta)$

$\sin(\theta) / \cos(\theta) = \mu = \tan(\theta)$



Rotational Force



Kinetic energy = $\frac{1}{2} \times I \times \omega^2$

Power = $\tau \times \omega$ (Nm x rad / sec)

Torque = F(force perpendicular) x d(distance of the lever arm)

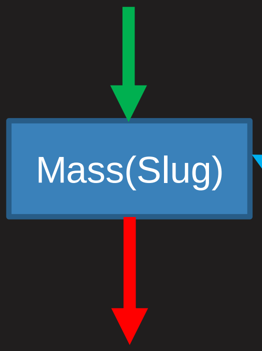
lbf-in = 0.112984829 N-m

lbf-ft = 1.36 N-m

(2*Pi) / 60 RPM = 1 rad/ sec
1RPM = 0.105 rad / sec
1 MPH = 0.45 m / sec

Weight(lb) is a Force

g = gravity ($9.8 m/s^2$)



Weight(lbs) = m x g

Since weight is a force its SI unit is N
1 N = 0.2248 lbf
1 lbf = 4.448 N

Note:
1 slug = 14.5932 Kg
1 slug = 32.1740 lbm
1 kg = 2.2046 lbm
1 lbm = 0.4536 Kg

Standard g = $9.8 m/s^2$ or $32.2 ft/s^2$
($32.1740486 ft/s^2$ or $9.80665 m/s^2$)

Under standard gravity: 1lbm weights 1lbf

FIRST Force Generation Options

Pneumatic
- Air Cylinder
  - 2 position action
  - Slow movement (Time Required: pressurizing air lines)

Electromagnetic
- Solenoid → Air Cylinder
- DC motor
  - Variable position
  - Slow movement (Time Required: create mag field, overcome inertia)

Mechanical
- Spring
  - Push/pull action
  - Fast movement (stored energy)

Mechanical Advantage

Mechanical Advantage (MA) is a measure of force amplification achieved by using a tool

Wikipedia

$MA = Force_{out} / Force_{in}$

However, Conservation of energy: Energy In = Energy Out + Losses

Simple machine tools:

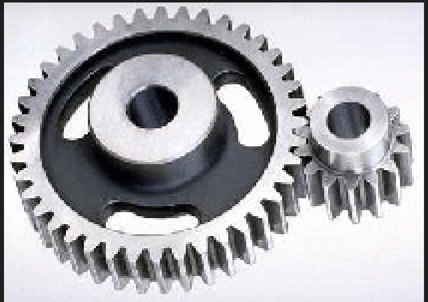
Lever	MA = length in / length out
Ramp	MA = ramp length / ramp height
Pulley	MA = effort distance / Load distance
Screw	MA = Rotation / Pitch
Wheel and axle	MA = Wheel radius / Axle radius

Note:

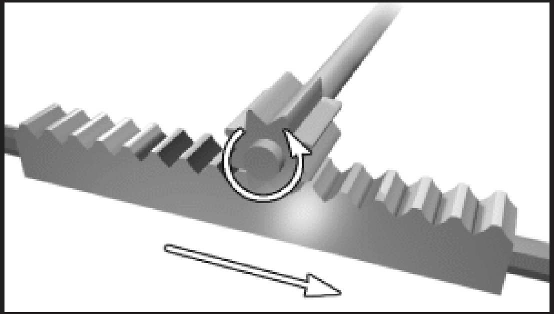
Wedge – double incline plane

Gear – series of levers

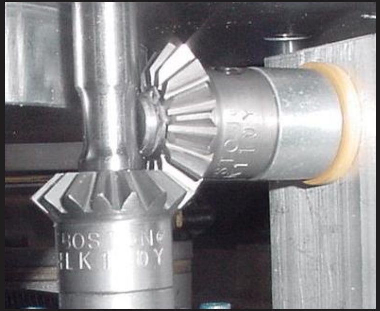
MA-Gear Types



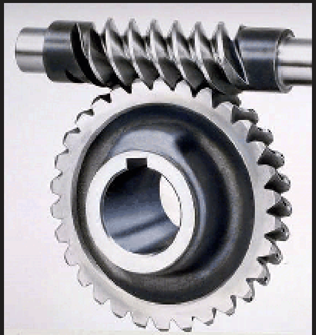
Spur



Rack and Pinon



Bevel



Worm

Gear Types:

Spur – most common

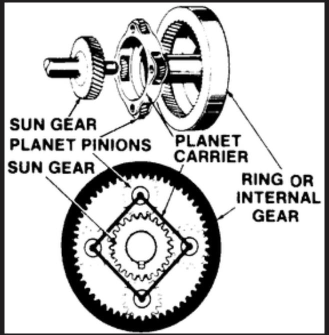
Helical - less noise than a spur

Rack & Pinion – rotary to linear

Worm gear – analogous to a screw – acts as a brake when stopped

Internal gear – used in planetary gear arrangement

Bevel gear – transmits motion at 90 degrees



Planetary

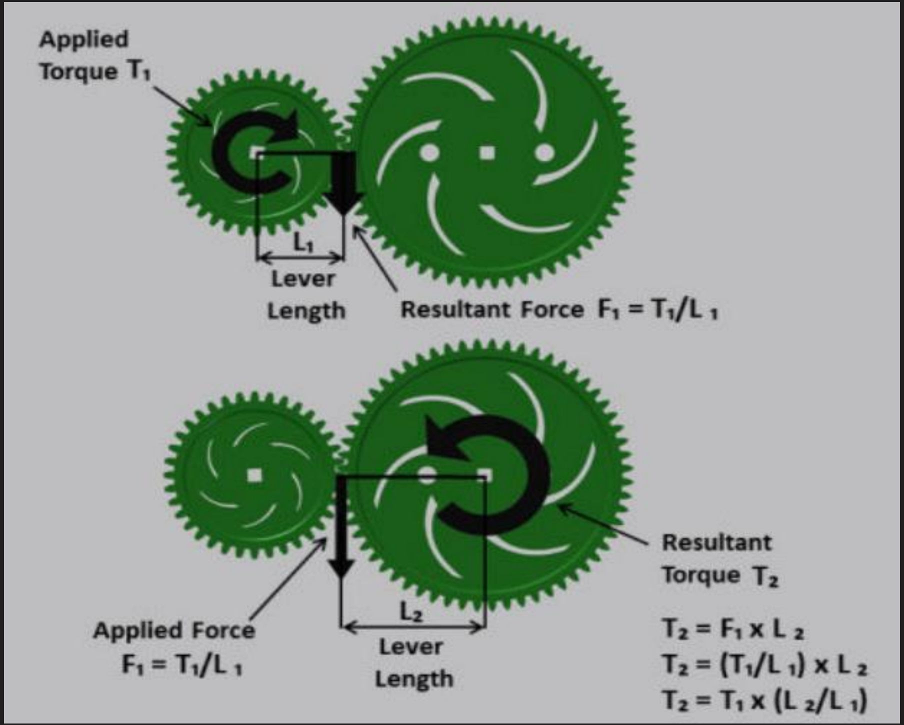
MA – Why use gearing?

A motor is more efficient at high speeds in that it uses less current to deliver power. As we will see, gearing allows the user to swap torque and speed.

However:

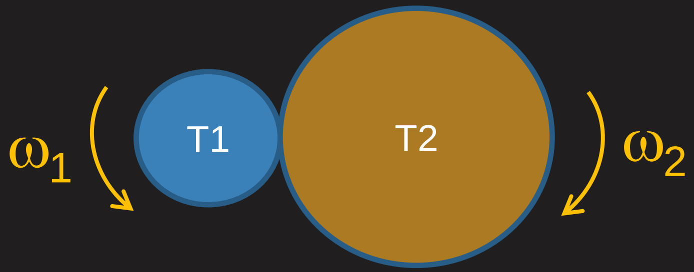
energy in = energy out + losses

MA-Gearing is a series of levers



Vex Robotics

Gears – Gear Ratio



Gear Ratio(N) = #Input turns / #Output turns

Gear Ratio(N) = radius2 / radius1

Gear Ratio(N) = #Teeth(T2) / #Teeth(T1)

N > 1:
- Decreased Speed
- Increased Torque

N < 1:
- Increased Speed
- Decreased Torque

Torque: $\tau_{out} = \tau_{in} \times N$

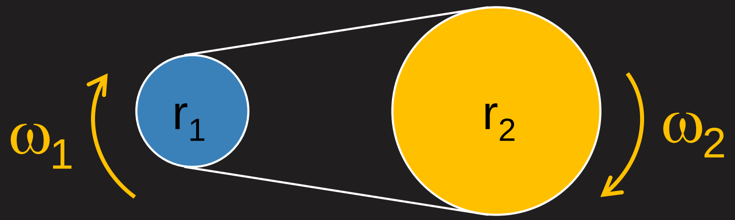
Speed: $\omega_{out} = \omega_{in} \times (1 / N)$

Gear Efficiency(η) $= P_{out} / P_{in}$

Torque: $\tau_{out} = \tau_{in} \times N \times \eta$

Speed: $\omega_{out} = \omega_{in} \times (1 / N) \times \eta$

MA – Gear Ratio: Belt / Chain Drive

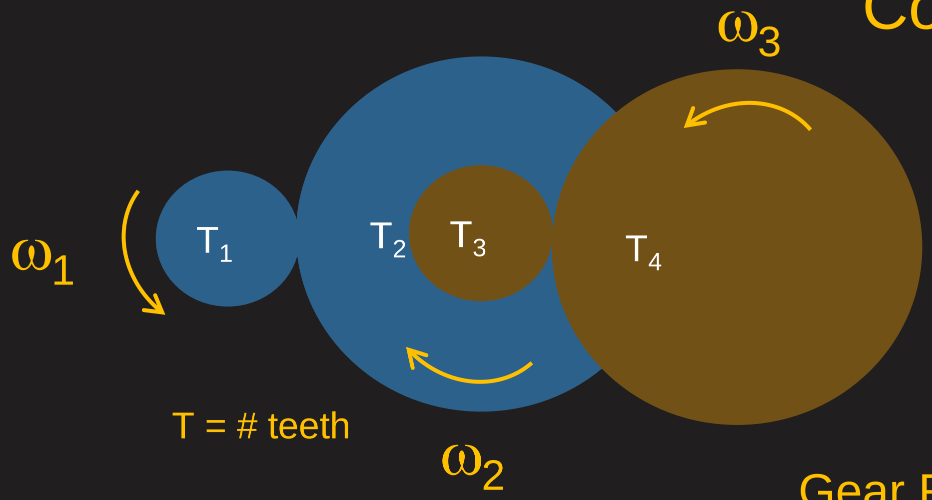


Gear Ratio(N) = Driven Pulley(r2) / Driving Pulley(r1)

Torque: $\tau_{out} = \tau_{in} \times N$

Speed: $\omega_{out} = \omega_{in} \times (1 / N)$

MA-Gear Train



Consecutive gear stages multiply:

Gear Ratio: $N_t = N_1 \times N_2 = (T_2 / T_1) \times (T_4 / T_3)$

Torque: $\tau_{out} = \tau_{in} \times N_t$

Speed: $\omega_{out} = \omega_{in} \times (1 / N_t)$

Torque: $\tau_{out} = \tau_{in} \times N_t \times \eta_1 \times \eta_2$

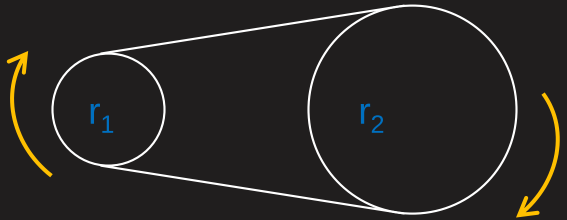
MA-Gear Efficiency

Remember, wear and lubrication will also dramatically affect gear efficiencies

1. Chain & Belt

   Efficiency ~ 85% - 98%

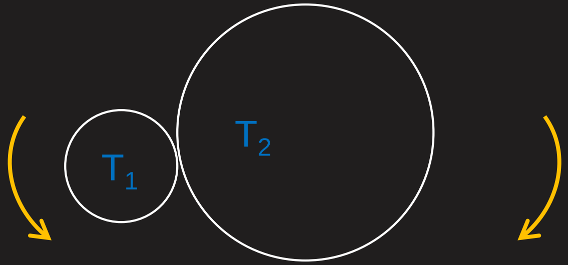
   GR N = r_2/r_1



2. Spur Gears

   Efficiency ~ 95% - 98%

   GR = T_2/T_1

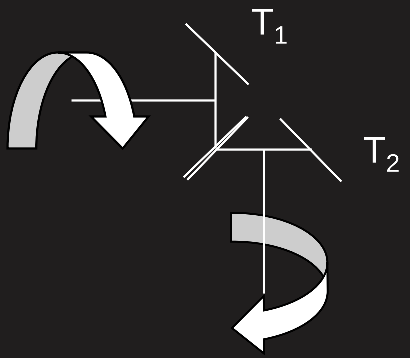


MA-Gear: Bevel/Worm Gear Efficiency

3. Bevel Gears

Efficiency ~ 90% - 95%

GR N = T_2/T_1



4. Worm Gears

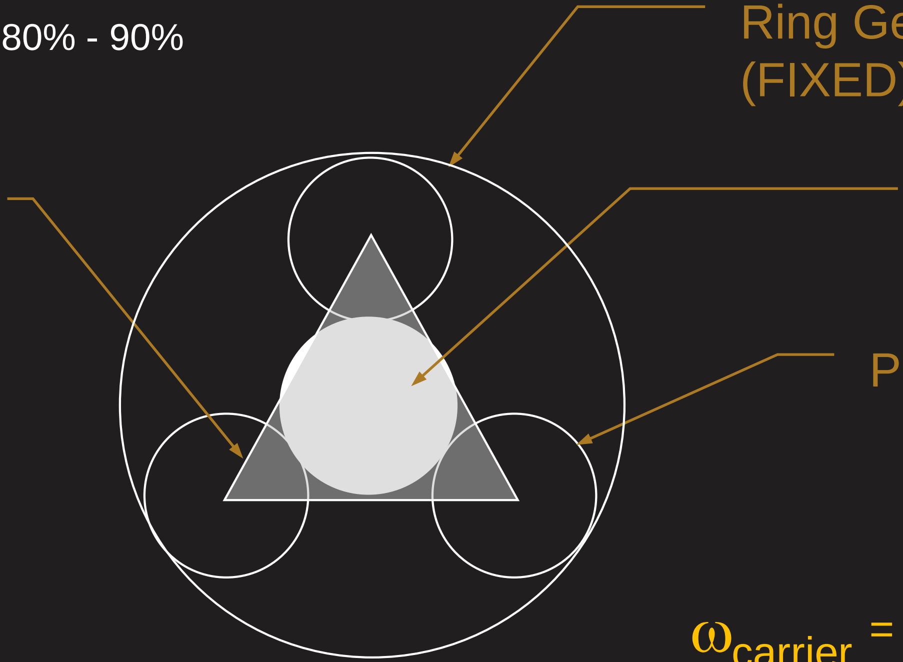
Efficiency ~ 40% - 70%

$$\text{GR N} = \frac{\text{\# Teeth on Worm Gear}}{\text{\# of Threads on worm}}$$

MA-Gear: Planetary Gear- Efficiency

5. Planetary Gears

Efficiency ~ 80% - 90%

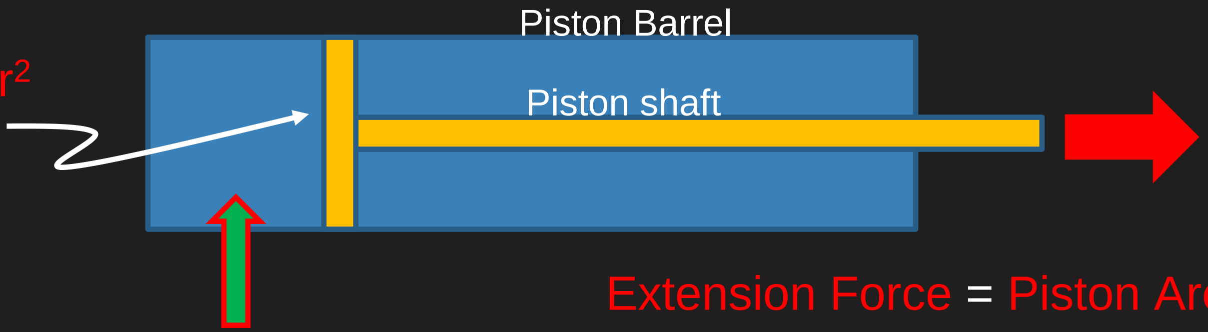


$$GR = \frac{\#teeth\_ring}{\#teeth\_sun} + 1$$

$$\omega_{carrier} = (1 + (T_1 / T_2)) \times \omega_{sun}$$

MA-Piston

Piston Area = π x r^2



Extension Force = Piston Area x PSI

Note:
Retraction Force = (Piston Area – Piston Shaft Area) x PSI

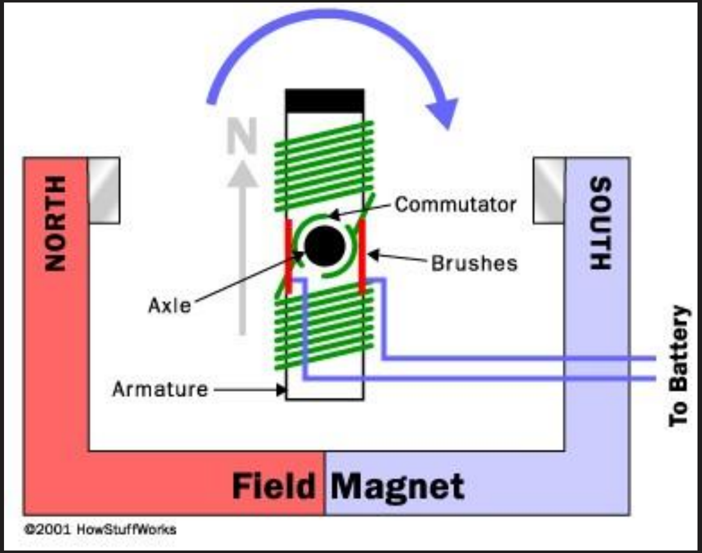
Motors

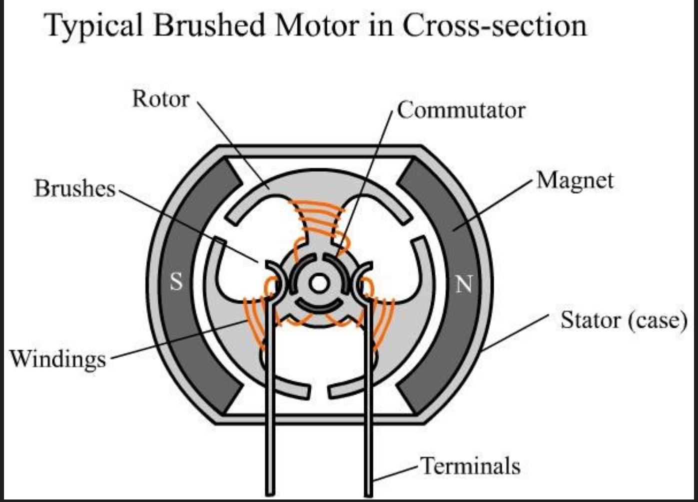
Goals of this section:

1 Motor design and FIRST control system layout
2 FRC acceptable motors
3 DC motor specs and speed-torque curves
4 Electrical circuit resistance
5 Motor selection process

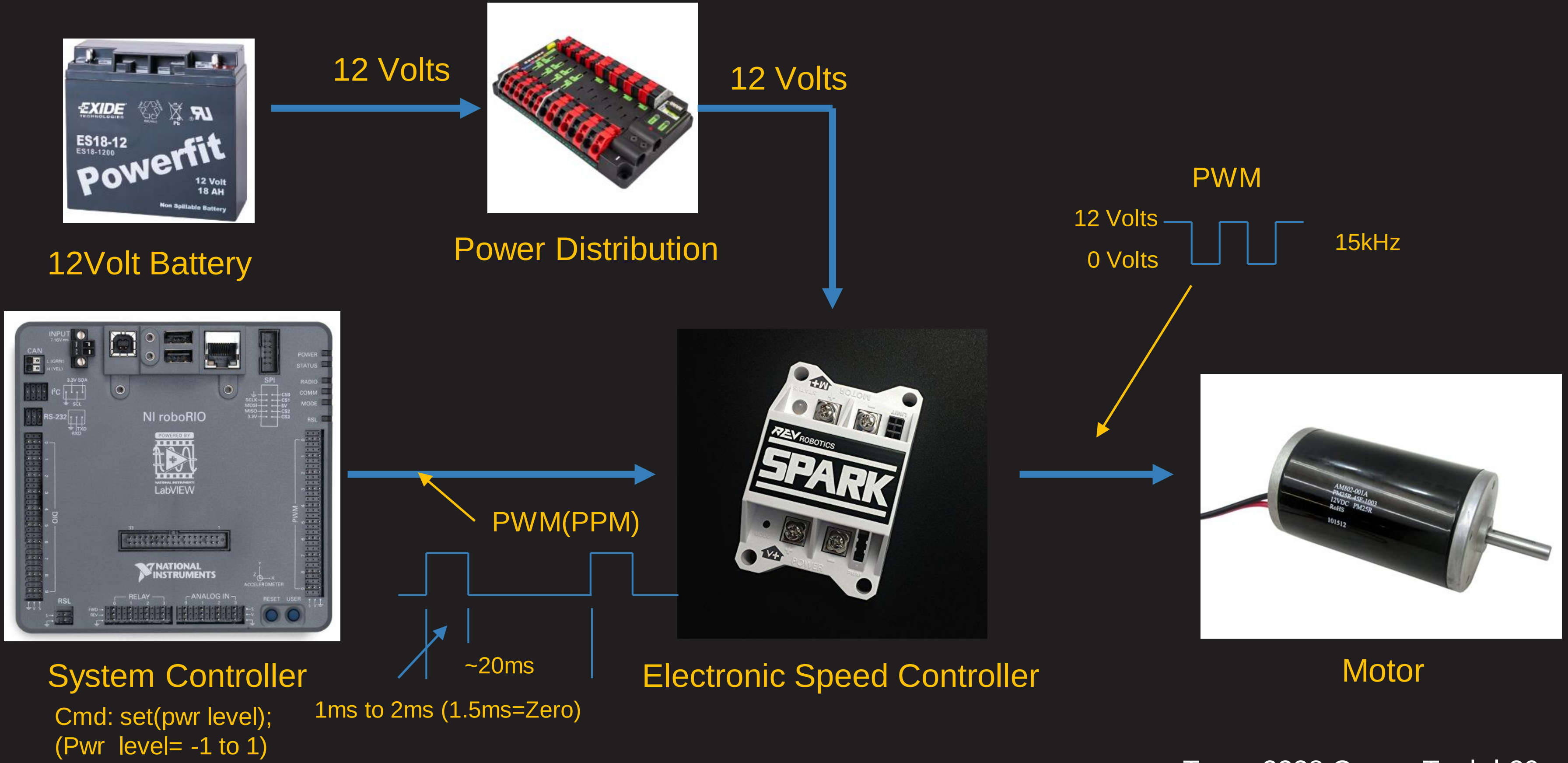
Motor Design

A motor is a special electromagnet that changes electrical energy to rotary mechanical energy to produce torque that can do work





FIRST Motor Control Components/Process



FRC Motors

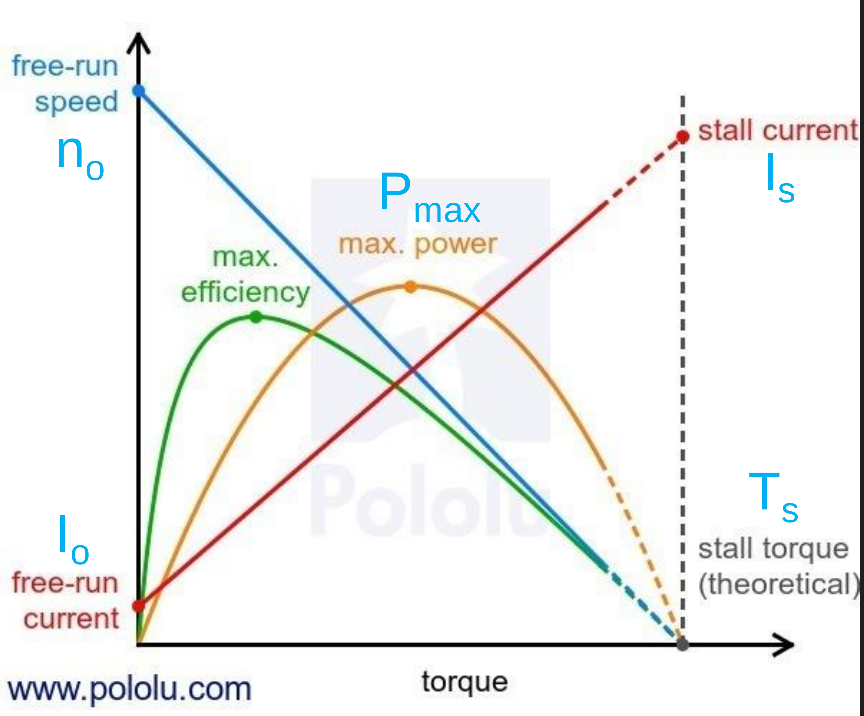
2015 FRC Motor Information

Make	Name	Part Number	Max Power (W)	Stall Torque (oz-in)	Free Speed (rpm)	Free Current (A)	Stall Current (A)	Weight (lbs)
AndyMark	9015 Motor	am-0912	179.49	60.64	16000	1.2	63.80	0.50
AndyMark	RS775-5 Motor	am-2161	36.91	35.00	5700	0.6	22.00	0.81
AndyMark	RS775-125 Motor	am-2194	36.91	35.00	5700	0.6	22.00	0.78
AndyMark	Snow Blower Motor	am-2235	29.60	1600.00	100	5.0	24.00	1.11
BaneBots	RS-550 Motor	M5-RS550-12 M5-RS550-12-B	245.83	68.85	19300	1.4	85.00	0.48
BaneBots	RS-775 Motor	M7-RS775-18	266.79	110.93	13000	1.8	86.70	0.74
Bosch	Spindle Drive Motor	6004 RA3 353-01	N/A	N/A	6500	2.5	21.00	1.10
Denso	Window Motor	262100-3030	23.33	1501.10	84	1.8	18.60	1.02
Denso	Window Motor	262100-3040	23.33	1501.10	84	1.8	21.00	1.02
Denso	Throttle Motor	AE235100-0160	18.04	18.40	5300	1.0	7.00	0.50
Varies	CIM Motor	Varies	337.34	343.40	5310	2.7	133.00	2.80
VEX	BAG Motor	217-3351	146.71	56.64	14000	1.8	41.00	0.71
VEX	Mini CIM Motor	217-3371	227.40	198.26	6200	1.5	86.00	2.16

Motor Characteristics

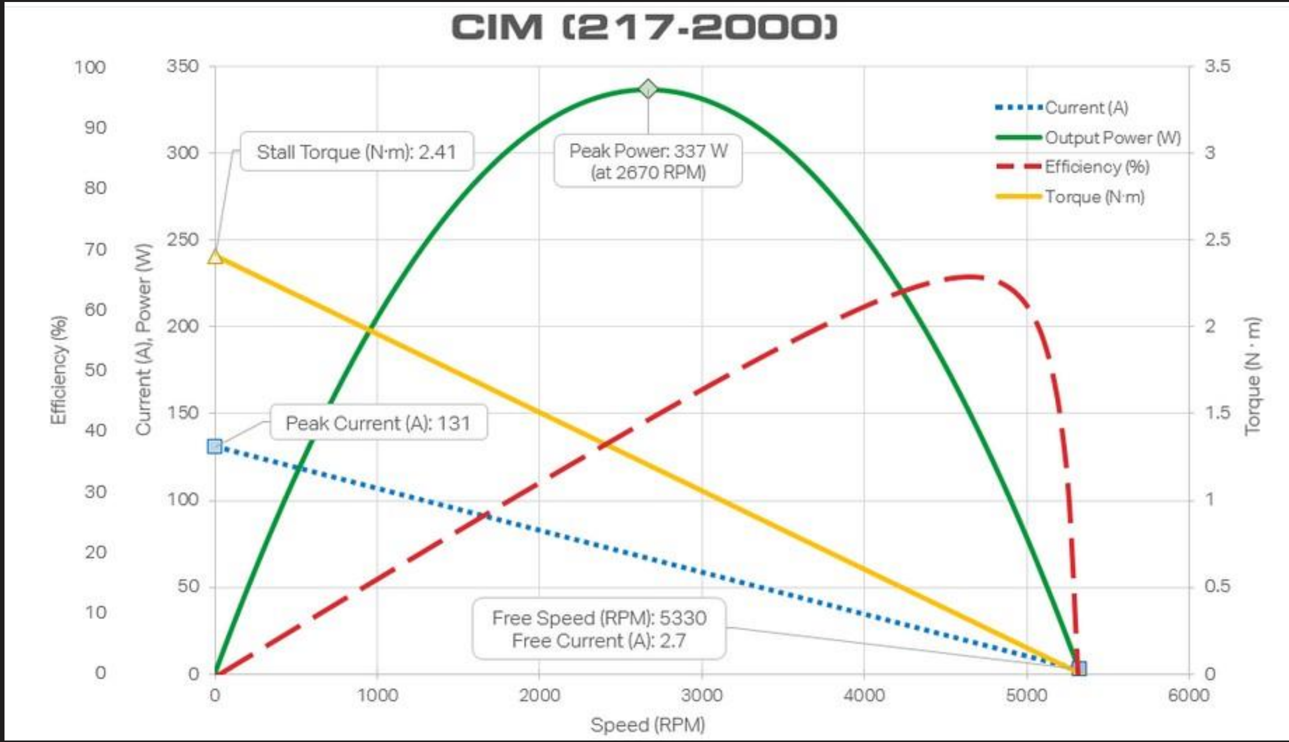
Motor Characteristics from Data Sheet

- Max Power
- Stall Torque
- Stall Current
- Free running Current
- Free running Speed

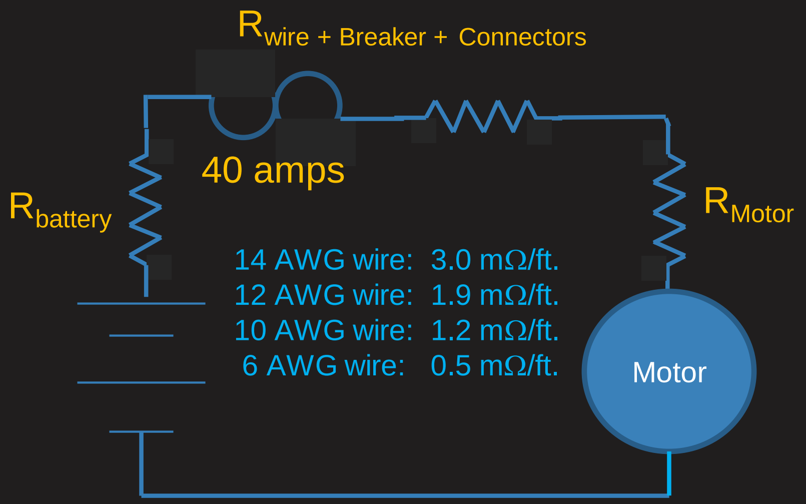


CIM Data from Vex

	Published Specification	Experimental Data
Free Speed (RPM)	5310 (+/- 10%)	5330
Free Current (A)	2.7	2.7
Maximum Power (W)	337	337
Stall Torque (N · m)	2.42	2.41
Stall Current (A)	133	131



Circuit resistance Matters



<u>System Resistance:</u>

Battery	0.012
Wires(10ft of 12AWG)	0.019
Breakers, connectors	0.020
Total	0.051

Motor(nom) – CIM 0.090 ohms

$R_m = V_{spec} / I_{stall} = 12 / 133 = 0.090$

Motor(hot-increase 40% - CIM 0.126

Total System 0.177

Additional resistance reduces stall torque proportionally

By $R_{motor} / R_{system} = 0.126 / 0.177 = 0.712$

$\tau_{stall} = 343.4 \text{oz-in} \times 0.712 = 244.5 \text{ oz-in}$

Available Motor Power

Facts:

1) Each motor fused for 40 amps
2) The batteries start out between 13-14v fully charged and end up around 11V when mostly discharged (empty)

A) Available electrical power.

11v*40A = 440 Electrical Watts *per motor*

B) most motors are 40-60% efficient when converting electrical energy to mechanical energy. Maximum sustainable mechanical power available per motor:

440Watts per motor * 0.4 = 176Watts

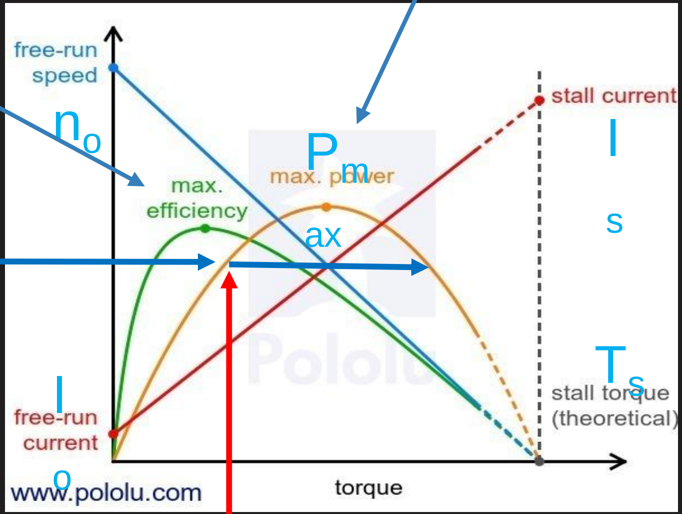
Motor Selection

Max Efficiency: ~25% Stall Torque or ~60% Max Power

Max Power: 50% Stall Torque, ~ 50% Stall Current, and 50% Free-running speed

Power is available at 2 different operating conditions:

1 High speed / low torque
2 Low speed / high torque



Select this power point for design:

1) For lower current draw
2) Use of mechanical advantage to regain torque

Best practices

1) Operate motor on left side of performance map (high speed / low torque)
2) Consider space and weight of motors in robot design
3) Air-cooled motors cannot operate near stall for more than a few seconds
4) Less gear trains better energy transfer
5) High gear: 14-16 ft/sec, low gear: 5-6 ft/sec
6) Reduce side load on motor output shaft
7) Use springs to balance motor energy

Motor Selection Process

1) Define the mechanical system
2) Convert all parameters to SI units
3) Determine Power to accomplish task
4) Find motor for application (FIRST approved Motors)
5) Determine mechanical advantage needed
6) Order motor and gear box

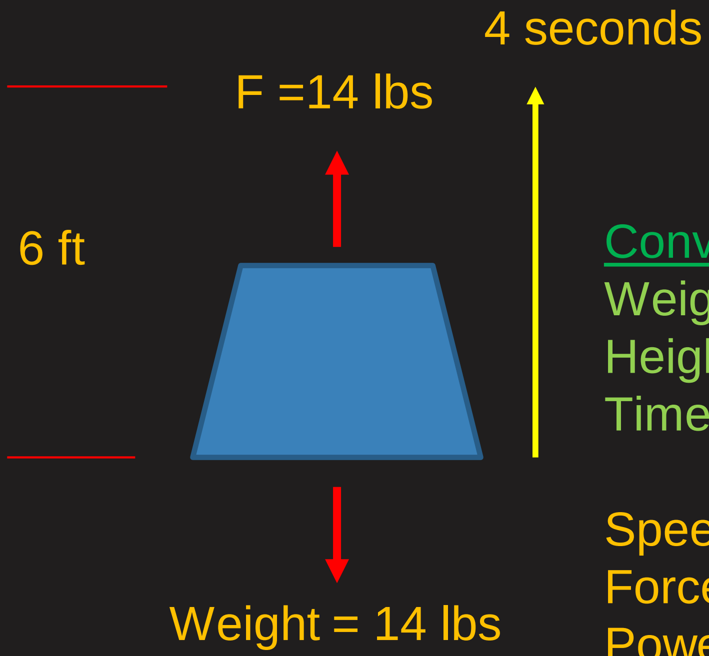
Work examples

Typical FIRST robotics work calculations:

1 Lifting a weight
2 Lifting a weight with a winch
3 Lifting a robot
4 Moving a robot
5 Lifting an object with an arm
6 Moving an object with a screw

Work: Lift a weight

1 kg = 2.2 lbm | 1 lbm = 0.4536 kg
1 m = 3.281 ft | 1 ft = 0.3048 m
Standard gravity g = 9.8 m/s^2
1 N = 0.2248 lbf | 1 lbf = 4.448 N
1 Nm = 0.7376 ft-lbf | 1 ft-lbf = 1.3556 Nm
1ft-lbm / sec = 1.36 Watt
1 rad/sec = 0.1047 RPM

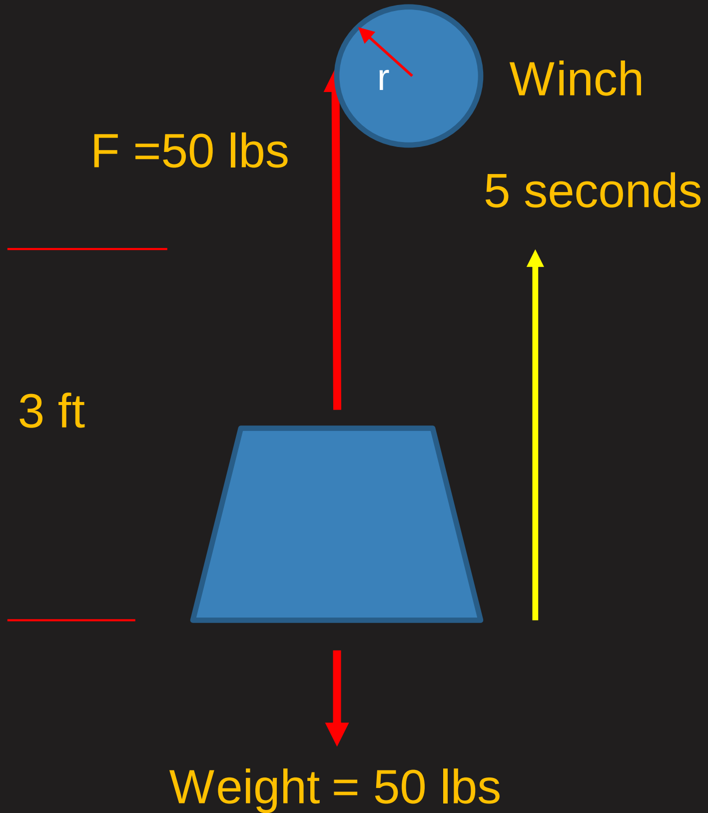


Convert to SI units:

Weight: **W** = 14 lb. =~ 62 N (F=ma)
Height: **h** = 6 ft. =~ 1.8 m
Time: **t** = 4 s

Speed: **v** = 1.8 m/ 4 s = 0.45 m/s
Force: **F** = **W** = 62 N
Power: **P** = **F** x **v** = 62 N x 0.45 m/s = 28 Nm/sec =28 W

Work/Power: Lift a weight (What is r)



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1ft-lbm / sec = 1.36 Watt
1 rad/sec = 0.1047 RPM

Power = ((50 lb)(3 ft)/5 sec)(1.36W / 1 ft-lbm/sec) =~ 40W

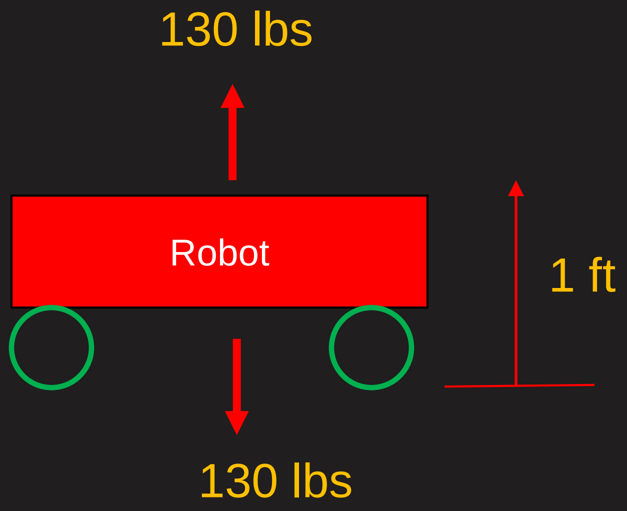
Convert to SI units:
Weight: **W** = 50 lb. =~ 222 N (F=ma)
Height: **h** = 3 ft. =~ 0.914 m
Time: **t** = 5 s

Speed: **v** = 0.914 m/ 5 s = 0.183 m/s
Force: **F** = **W** = 222 N
Power: **P** = **F** x **v** = 222 N x 0.183 m/s =~ 40 Nm/sec =40 W

A motor selected at 40W (~45% eff) is 100 in-lbs;
Thus r = 100in-lbs / 50 lbs = 2in

Work/Power: Lift robot

1 kg = 2.2 lbm | 1 lbm = 0.4536 kg
1 m = 3.281 ft | 1 ft = 0.3048 m
Standard gravity g = 9.8 m/s^2
1 N = 0.2248 lbf | 1 lbf = 4.448 N
1 Nm = 0.7376 ft-lbf | 1 ft-lbf = 1.3556 Nm
1ft-lbm / sec = 1.36 Watt
1 rad/sec = 0.1047 RPM



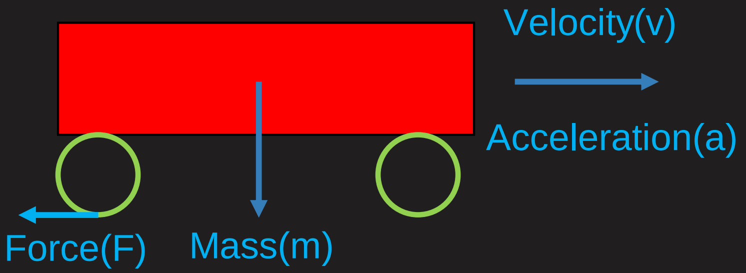
Convert to SI units:
W = 130 lbs = 580 N (F=ma)
H = 1 ft = 0.31 m

P = (F)orce x (v)elocity
For 2 seconds:
P = 580N x (0.31m / 2sec) = 87 Watts

For 4 seconds:
P = 580N x (0.31m / 4sec) = 45 Watts

Work/Power: Move a robot

1 kg = 2.2 lbm | 1 lbm = 0.4536 kg
1 m = 3.281 ft | 1 ft = 0.3048 m
Standard gravity g = 9.8 m/s^2
1 N = 0.2248 lbf | 1 lbf = 4.448 N
1 Nm = 0.7376 ft-lbf | 1 ft-lbf = 1.3556 Nm
1ft-lbm / sec = 1.36 Watt
1 rad/sec = 0.1047 RPM



Two wheels are driven

	CIM Ratio Aprox. Output Speeds (Loaded)	
4" Wheel	15.0 : 1 = 6 ft/s	5.13 : 1 = 16 ft/s
6" Wheel	16.4 : 1 = 8 ft/s	7.95 : 1 = 15.5 ft/s

Large wheels = faster, less torque
Smaller wheels = slower, more torque

Convert to SI units:

Mass: **m** = 150 lb. = 68 kg
Speed: **v** = 6 ft./s = 1.8 m/s
Acceleration: **a** = 1.8 m/s per sec = 1.8 m/s^2

Force = **m** x **a** = 68 kg x 1.8 m/s^2 = 122 N
Force from each wheel: **F** = 122 N / 2 = 61 N

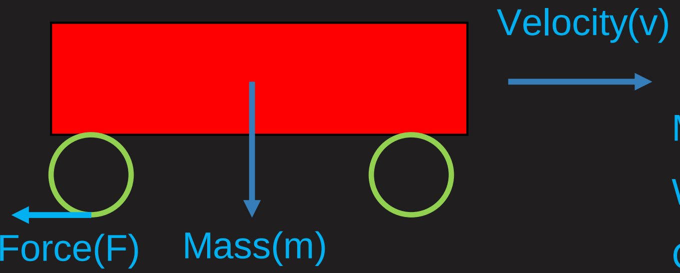
Power: **P** = **F** x **v** = 61 N x 1.8 m/s = 110 W

Work: Move a robot

Problem: (v)elocity = 1.8 m/s; (F)orce = 61 N

Motor selected: ω_{free} = 559 rad/sec, τ_{stall} = 1.2Nm

1 kg = 2.2 lbm | 1 lbm = 0.4536 kg
1 m = 3.281 ft | 1 ft = 0.3048 m
Standard gravity g = 9.8 m/s^2
1 N = 0.2248 lbf | 1 lbf = 4.448 N
1 Nm = 0.7376 ft-lbf | 1 ft-lbf = 1.3556 Nm
1ft-lbm / sec = 1.36 Watt
1 rad/sec = 0.1047 RPM | 1 RPM = 9.5493rad/sec



Two wheels are driven

8inch wheels: R_{wheel} = 4" = 0.1 m

Motor speed: $\omega_{motor} = \omega_{free} / 2 = 559$ rad/s / 2 = 280 rad/s

Wheel speed: $\omega_{motor} = \mathbf{v} / R_{wheel}$ = (1.8 m/s) / (0.1 m) = 18 rad/s

Gear ratio: $N_g = \omega_{motor} / \omega_{wheel}$ = (280 rad/s) / (18 rad/s) = 16

Usual limit per stage is 5:1 - need two stages.

Gear efficiency: $\eta_g = 0.9 \times 0.9 = 0.81$

Wheel torque:

$\tau_{wheel} = \eta_g \times N_g \times \tau_{stall} / 2 = 0.81 \times 16 \times 1.2$ Nm / 2 = 7.8 Nm

Force: $F = \tau_{wheel} / R_{wheel}$ = (7.8 Nm) / (0.1 m) = 78 N (OK)

Work: Lift weight with arm

1 kg = 2.2 lbm | 1 lbm = 0.4536 kg
1 m = 3.281 ft | 1 ft = 0.3048 m
Standard gravity g = 9.8 m/s^2
1 N = 0.2248 lbf | 1 lbf = 4.448 N
1 Nm = 0.7376 ft-lbf | 1 ft-lbf = 1.3556 Nm
1ft-lbm / sec = 1.36 Watt
1 rad/sec = 0.1047 RPM

Work = Force x Distance

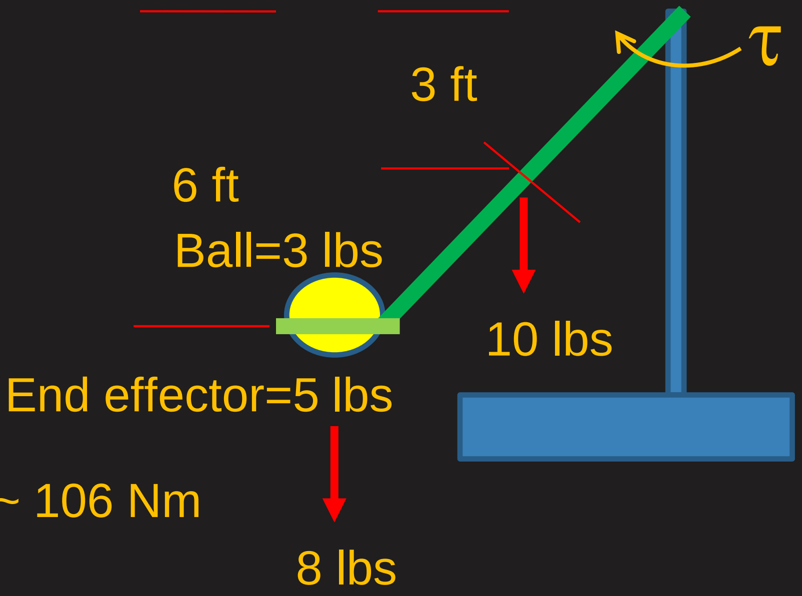
Work = F_1 x d_1 + F_2 x d_2

Convert to SI Units:

10lbs =~ 44N (F=ma)
8 lbs =~ 36N
3ft =~ 0.941m
6ft =~ 1.8m

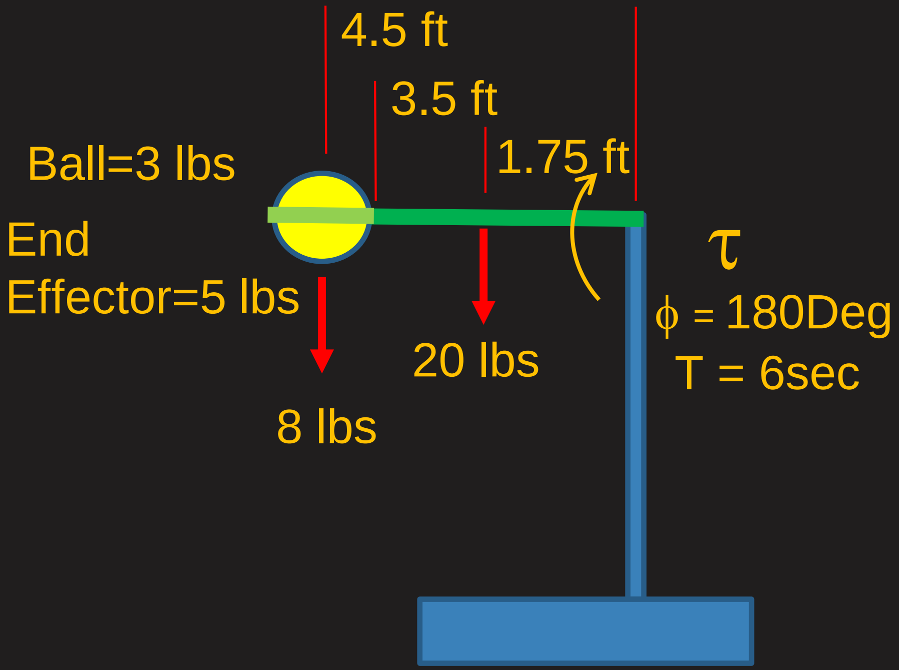
Work = 44N x 0.941m + 36N x 1.8m =~ 106 Nm

τ = 106Nm x 1.356 =~ 78 ft-lbs



(use center of gravity to determine distance)

Work: Lifting a Ball (part1)



(use center of gravity to determine distance)

1 kg = 2.2 lbm | 1 lbm = 0.4536 kg
1 m = 3.281 ft | 1 ft = 0.3048 m
Standard gravity g = 9.8 m/s^2
1 N = 0.2248 lbf | 1 lbf = 4.448 N
1 Nm = 0.7376 ft-lbf | 1 ft-lbf = 1.3556 Nm
1ft-lbm / sec = 1.36 Watt
1 rad/sec = 0.1047 RPM | 1 RPM = 9.5493rad/sec

Total torque = torque of ball + torque of arm
= (8 lbs X 4.5 ft + 20 lbs X 1.75 ft)
= 71ft-lbs = 852in-lbs =~ 96 Nm

Angular Velocity = 180 degrees / 6 sec.
= 5 RPM = 0.5 Rad/sec

Power = Torque X Angular Velocity
Power = 96 N-m X 0.5 Rad/sec = 48 Watt

Work: Lifting a Ball (part2)

Best to design a gear ratio such that the load reflected back to motor is around 20%~50% stall torque when motors are most happy.

CIM Motor selected: stall torque: 2.42Nm = 1.785 ft-lbs =~ 21 in-lbs

20%~50% stall torque = 4.2 in-lb~10 in-lb

Torque range = 852 in-lb / 4.2in-lb ~ 852 in-lb / 10 in-lb

Gear ratio required torque range = 203:1 ~ 85:1

We will run motor at 45% of stall torque with a little room before maximum motor power:
Working Torque = 21 in-lb * .45 =~ 9 in-lb

Gear ratio = 852 in-lb / 9 in-lb = 95:1

Work: Lifting a Ball (part3)

Gear box option for CIM motor 100:1 two stage planetary gear.
Efficiency = 85%

Effective gear ratio = 10 x 0.85 x 10 x 0.85 = 72:1

Effective power = motor power * total component efficiency…
(We will just consider the gears' efficiency for this purpose)
.CIM 337W :
Effective power = 337W*.85*.85= 243.5W

Note: Marginal system – Improvements

1) Add torsion spring or surgical tubing to assist raising ball
2) Add chain drive with gear ratio > 1
3) Add another CIM/gearbox to other end of shaft (torque adds)

Work: Screw example

Problem: screw (v)elocity = 0.45 m/s and need a (F)orce = 61 N

Selected motor: ω_{free} = 2513rad/sec, τ_{stall} = 0.28Nm

Screw speed = motor speed: ω_{screw} = ω_{free} / 2 = 2513 rad/s / 2 = 1256 rad/s

ω_{screw} = (1256 rad/s) / (2π rad/revolution) = 200 rev./s

τ_{screw} = τ_{motor} = τ_{stall} / 2 = 0.28 Nm / 2 = 0.14 Nm

Screw pitch: p = v / ω_{screw} = (0.45 m/s) / (200 rev./s) = 0.00225 m/rev. = 0.00036 m/rad

p = 11 threads per inch

Force: (Assume screw efficiency = 20%)

F = η_g x τ_{screw} / p = (0.2 x 0.14 Nm) / (0.00036 m/rad) = 78 N (OK)