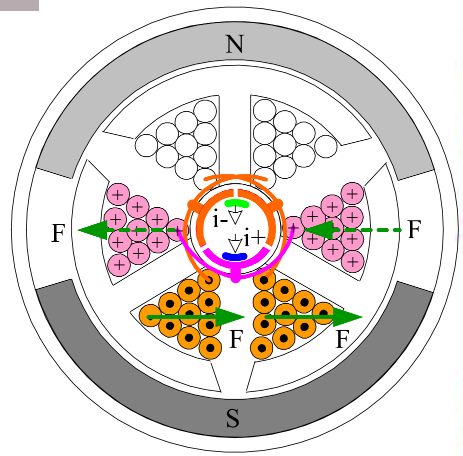
FUNdaMENTALS of Design

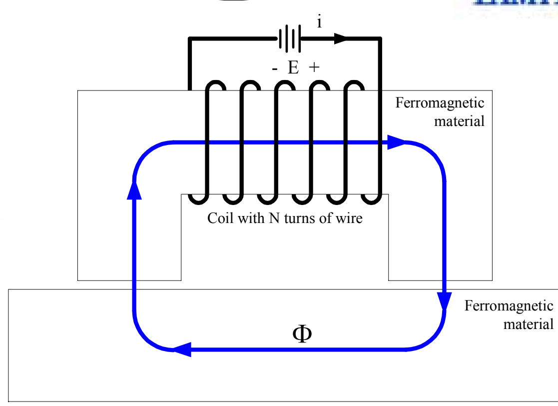
Topic 7
Power Systems

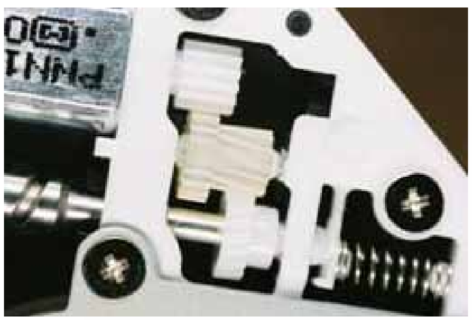

Topic 7
Power Systems

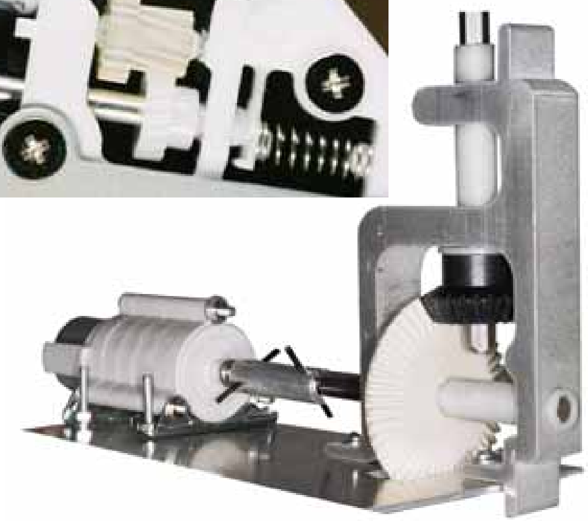
Topics:

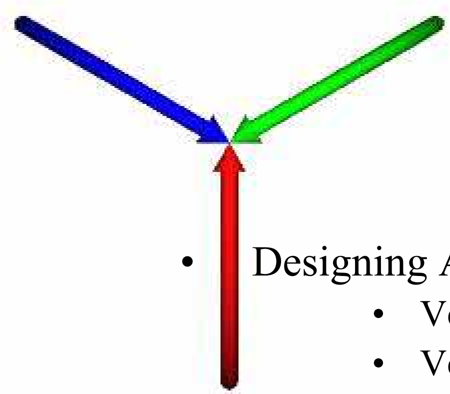
- Systems Engineering
- Electricity & Magnetism
- Magnetic Circuits
- Electric Motors
- Energy Supplies
- Pneumatic Systems
- Power Budgets



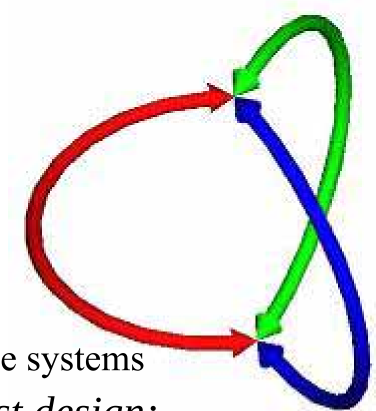




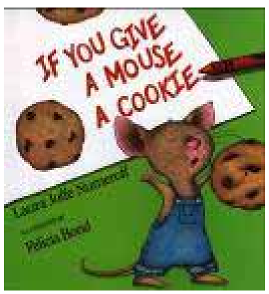


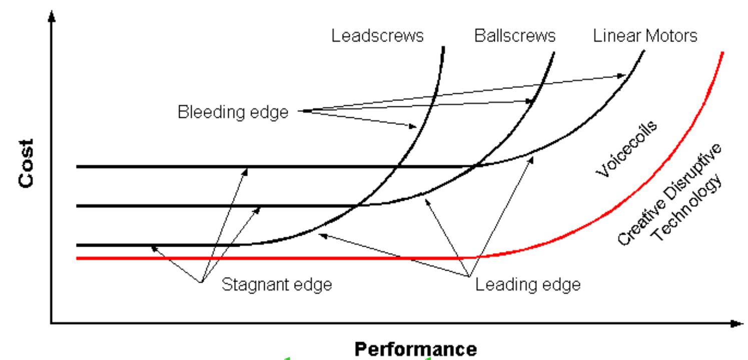


Systems Engineering

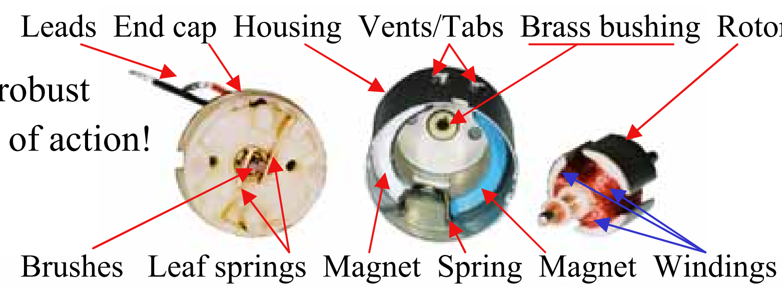


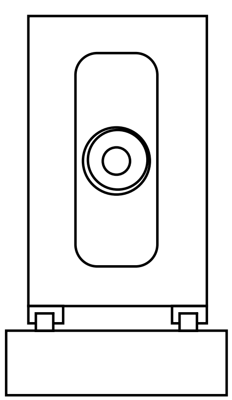
- Designing Actuators into/for a machine requires a system's approach
  - Very few things are as simple as they may seem: *The details matter!*
  - Very few things are so complex that they cannot be decomposed into simple systems
- Three fundamental elements, *blended in appropriate amounts*, yield a *robust design:*

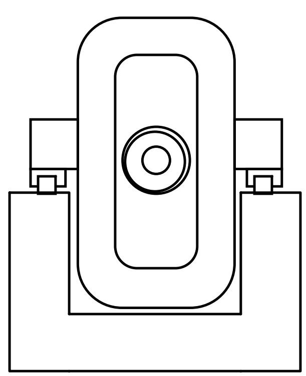


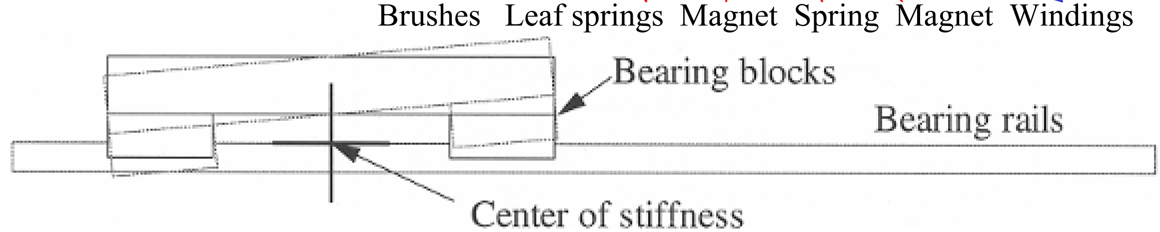


  - **Mechanical**
    - The interface to the physical world
  - **Electronics/Controls**
    - Sensors gather data and send it to the software
    - Amplifiers receive signals from the software
    - Motors receive power from the amplifiers
  - **Software/Strategy**
    - The logic of how the device processes inputs and creates outputs to the control system
  - ***The design process for each element are very similar!***
- Design for Robustness!
  - A deterministically designed system is likely to be robust
    - Actuators should be mounted near the centers of action!



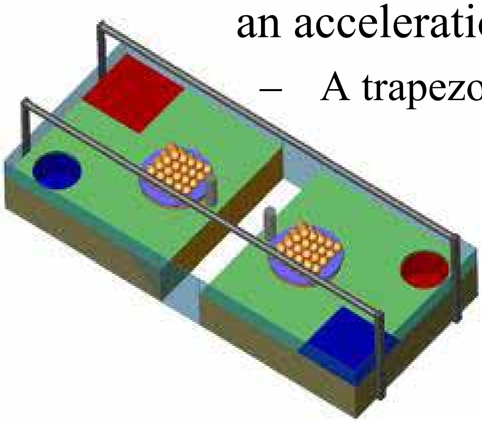


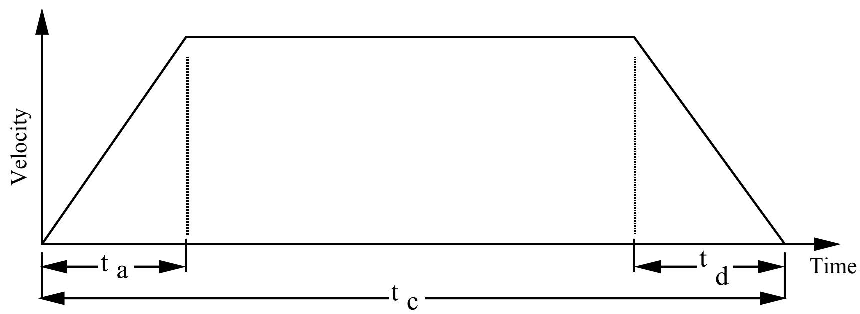


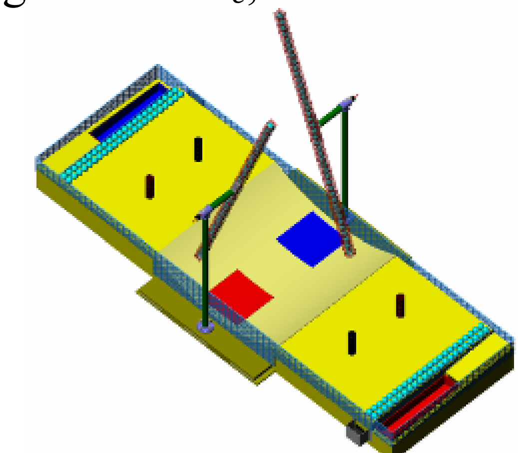


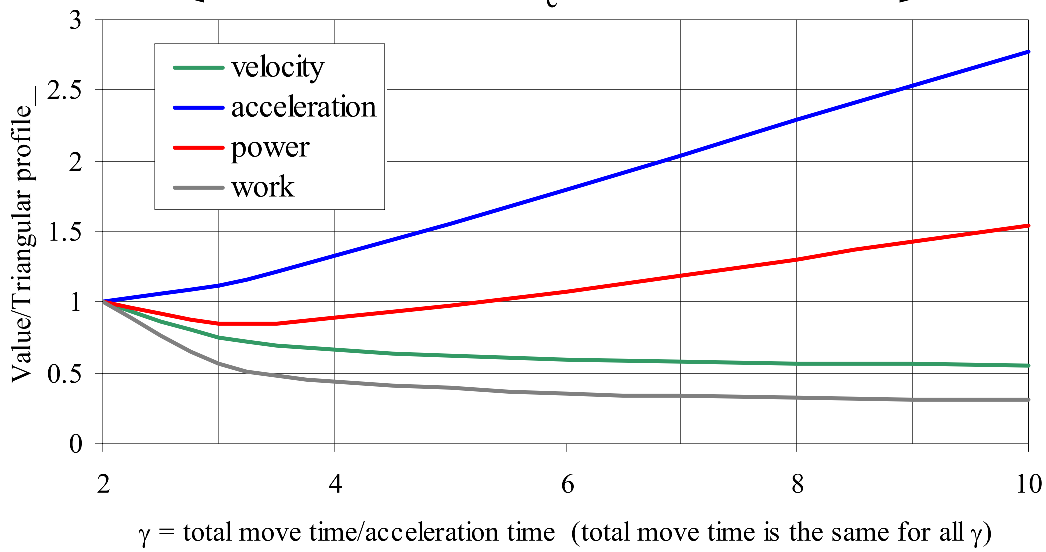
Systems Engineering: *Transmissions*

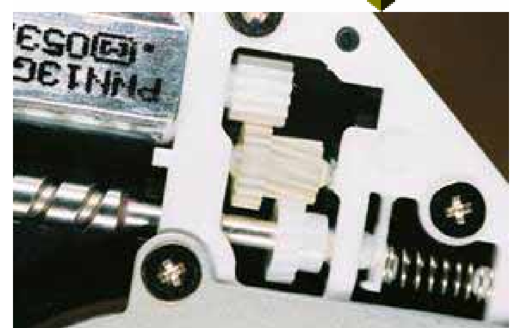
- A transmission is used to convert power from one form into another
  - E.g., rotary to linear motion, low-torque high-speed to high-torque low-speed
- To move a specified inertia m (J) a specified distance D in a given time t_c, with an acceleration time t_a
  - A trapezoidal velocity profile is generally very efficient

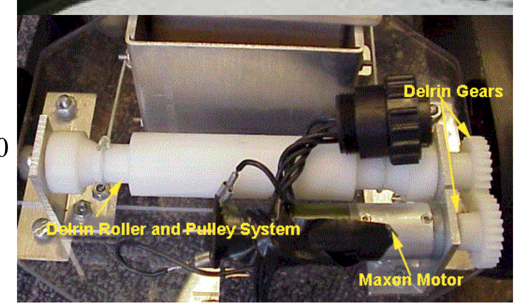




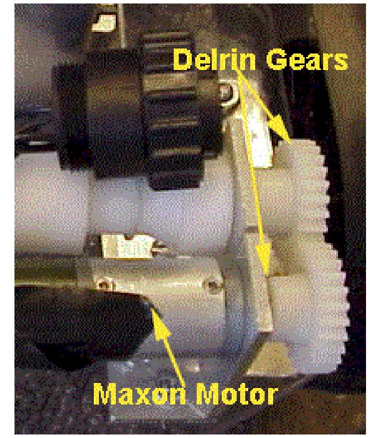








Systems Engineering: "*Optimal*" *Transmission Ratio*

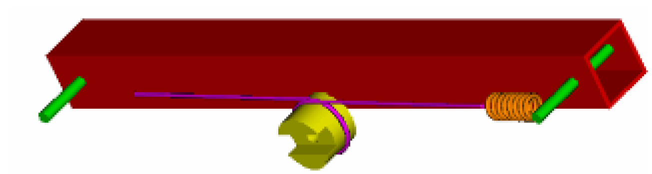


- The "optimal" transmission ratio most efficiently distributes power to the motor/drivetrain and the load, which are connected and must accelerate together
  - Assume mks (meters, kilograms, seconds) units
  - The motor speed ω_{motor} (rpm) to create rotational speed ω_{load} is:

$$\omega_{motor} = \omega_{load}\sqrt{\frac{J_{load}}{J_{motor}}} \Rightarrow n_{\text{transmission ratio}} = \sqrt{\frac{J_{load}}{J_{motor}}}$$

  - For a friction or belt drive system, the motor speed ω_{motor} (rpm) to create linear speed v_{linear} (m/s) is:

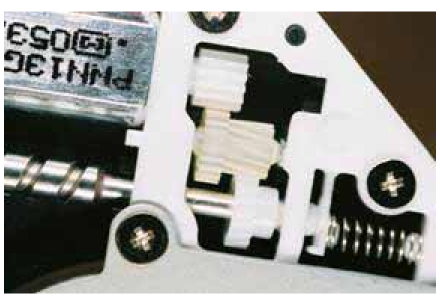
$$\omega_{motor} = \frac{30 v_{load}}{\pi}\sqrt{\frac{m_{load}}{J_{motor}}} \Rightarrow r_{pulley} = \sqrt{\frac{J_{motor}}{m_{load}}}$$



    - The optimal transmission ratio to be placed between a motor and a selected pulley is found by assuming the load inertia is:

$$J_{load} = r_{pulley}^2 m_{load} + J_{roller} \qquad J_{motor} = J_{motor\_rotor} + J_{transmission}$$

  - For a leadscrew driven carriage with lead λ (m traveled/revolution), the motor speed w_{motor} (rpm) to create linear speed v_{linear} (m/s) is:



$$\omega_{motor} = \frac{60 \times 1000 \times v_{load}}{2\pi}\sqrt{\frac{m_{load}}{J_{motor} + J_{leadscrew}}}$$

$$\lambda(mm) = 1000\sqrt{\frac{J_{motor} + J_{leadscrew}}{m_{load}}}$$

Georg Ohm (1789-1854)

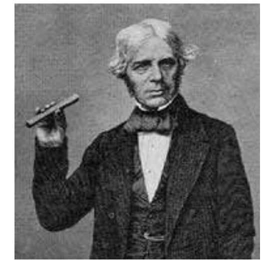
Hans Oersted (1771-1851)

Gustav Kirchoff (1824-1887)

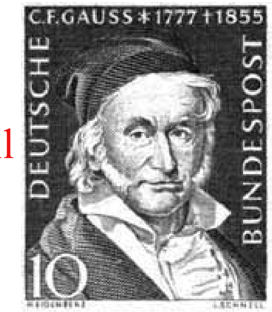
Electricity & Magnetism: *A New Revolution*

- Ohm's law:
  - Voltage (*electromotive force*) in a circuit = *current* x *resistance* (E = IR)
  - The *magnetomotive force* F_m (*MMF*) in a magnetic circuit is proportional to the *magnetic flux* Φ (*flux*) and the *reluctance* R ($F_m = \Phi R$)
- Kirchoff's current and voltage laws:
  - The sum of all currents (*fluxes*) flowing into a node is zero
  - The sum of all voltage drops (*MMF*) in a closed loop equals zero
- Faraday's law of electromagnetic induction:
  - Coils of wire and magnets interact to create electric and magnetic fields
- Ampere's law:
  - An "electromotive force", such as created by current passing through a coil of wire, *forces* a magnetic field through a magnetic circuit
- Gauss's law for magnetism:
  - Magnetic fields have North & South poles between which the field flows

André Ampère (1775-1836)



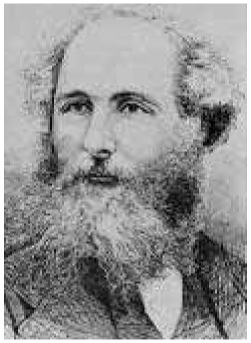
Michael Faraday (1791-1867)

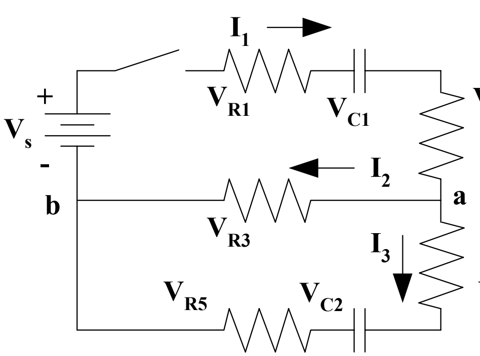


Johann Carl Friedrich Gauss (1777-1855)

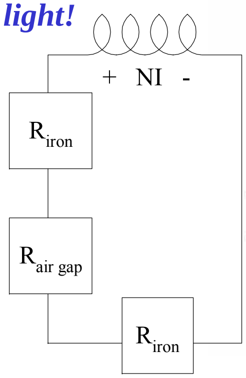
James Clerk Maxwell (1831-1879)

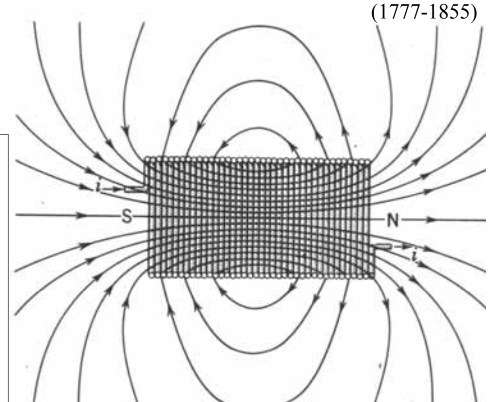
And then there was (an understanding of) light!





$$V_S = V_{R1} + V_{C1} + V_{R2} + V_{R3}$$
$$0 = V_{R3} + V_{R4} + V_{C2} + V_{R5}$$
$$I_1 = I_2 + I_3$$

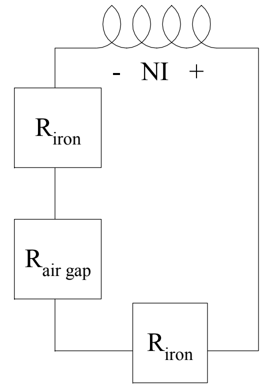


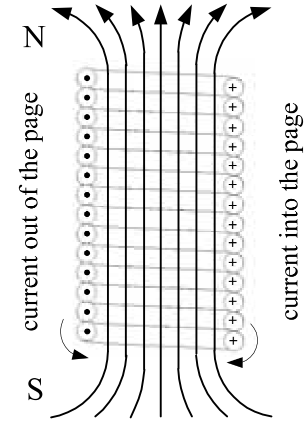


From D. Halliday & R. Resnick, *Physics Parts I & II Combined 3rd edition*

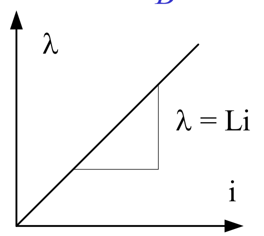
Electricity & Magnetism: ***FUN**da**MENTAL** Principles*

- Faraday's law of electromagnetic induction:
  - A Force F is required to move a conductor of length L carrying a current i through a magnetic field of strength B ($F = BLi$)
  - A magnet that moves in a coil causes a potential difference at the terminals of the coil
    - Current that flows through a coil, creates a magnetic field
      - The time varying change in a magnetic field Φ_B induces an electromotive force E:

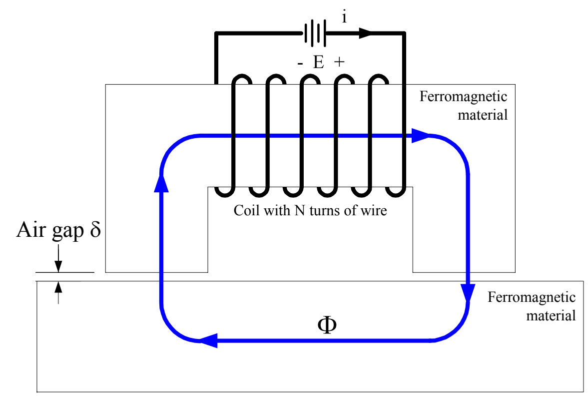




$$\oint \mathbf{E}\cdot d\mathbf{l} = -\frac{d\mathbf{\Phi_B}}{dt}$$

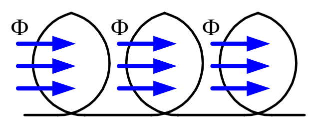


Definition of inductance L

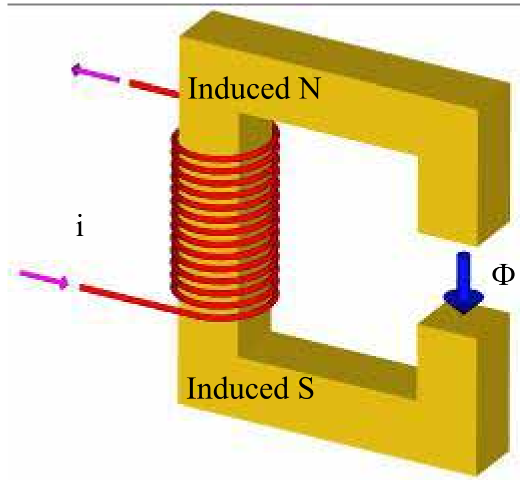


- Ampere's law:
  - The product of the magnetic field intensity H and length in a circuit equals the magnetomotive force:

$$\oint \mathbf{H}\cdot d\mathbf{l} = Ni = F_m$$



Flux linkage $\lambda = N\Phi$: N turns of a coil, in series with each other and linked together by magnetic flux Φ



- Gauss's law for magnetism:
  - The total magnetic flux ($\Phi = B*A_{area}$) across a closed boundary is zero (there are no magnetic monopoles):

$$\oint \mathbf{B}\cdot d\mathbf{S} = 0$$

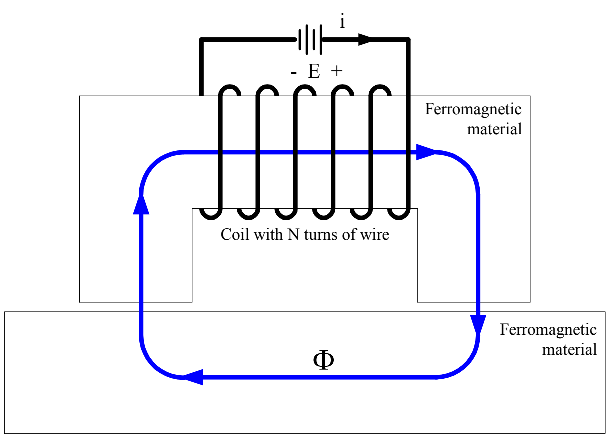
Magnetic Circuits

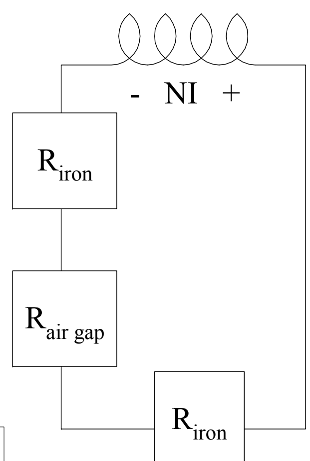
- Magnetic flux Φ flows in a circuit, just like electricity:
  - Permeability $\mu = B/H$: ability of a magnetic field to permeate (flow) through a material
  - $\mu_0 = 4\pi \times 10^{-7}$ (tesla-meter/ampere) = permeability of free space and non-magnetic materials
  - $\mu_r = \mu / \mu_0$ = relative permeability
  - Reluctance R is a measure of the resistance to flow of magnetic flux through a particular piece of material:

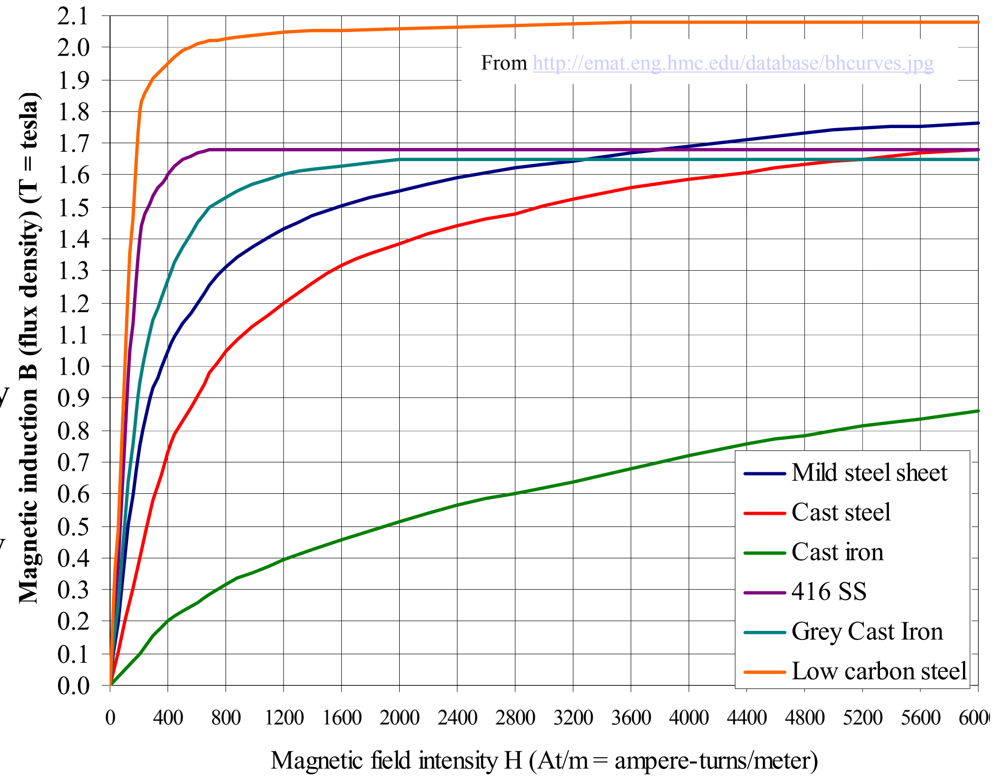
$$R = \frac{L_{\text{total path length in the material}}}{\mu A_{\text{cross sectional area along the path}}}$$

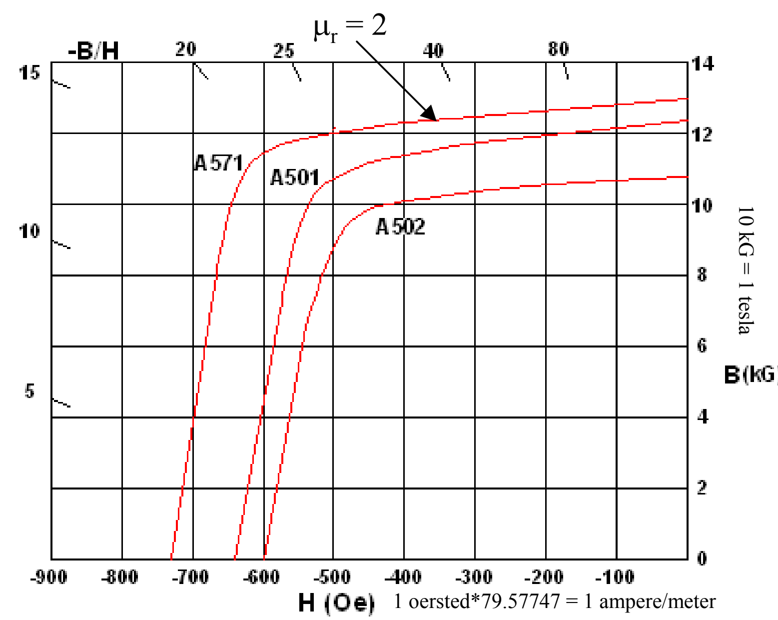
  - Attraction force F_{MT} across an air gap:

$$F_{MT} = \frac{B^2 A}{2\mu_o} = \frac{\Phi^2}{2\mu_o A}$$



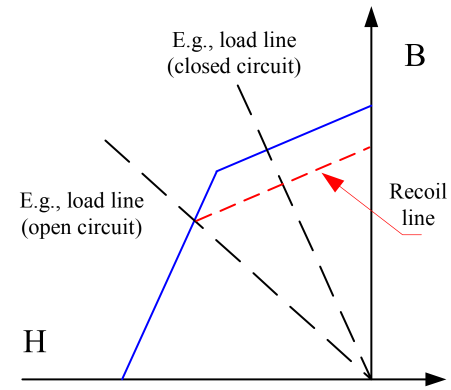




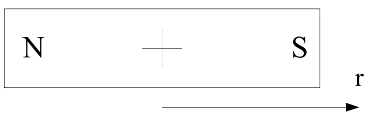


Alnico A501 from http://www.mceproducts.com/materials/Alnico_Details.asp?id=1047

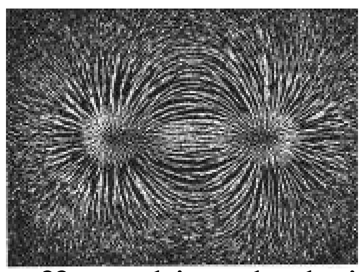
Magnetic Circuits: *Permanent Magnets*



- Permanent magnets provide magnetic flux which flows from their *North* pole to their *South* pole
  - In a circuit, they act as a "voltage" source, $MMF = F_m = BL/\mu_o$
  - The "current" (flux density), $B = \Phi/A$, associated with the "voltage" depends on the rest of the circuit
  - If too much "current" is drawn, they will demagnetize
- Flux density in space of a dipole along its axis a large distance from its center (NiA=Ampere-meter²):

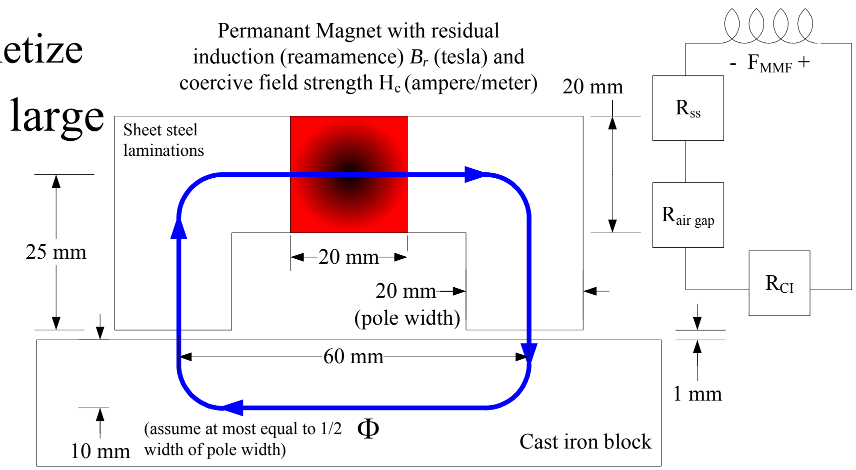


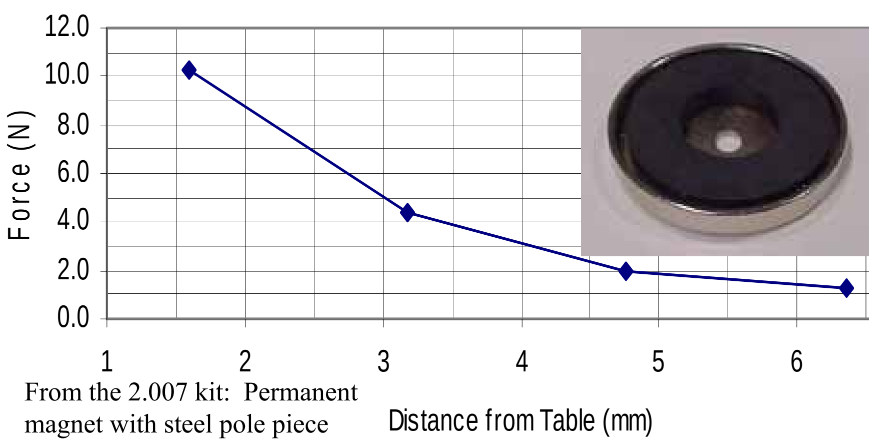
$$B\,(tesla) = \frac{\mu_o NiA}{2\pi r^3}$$



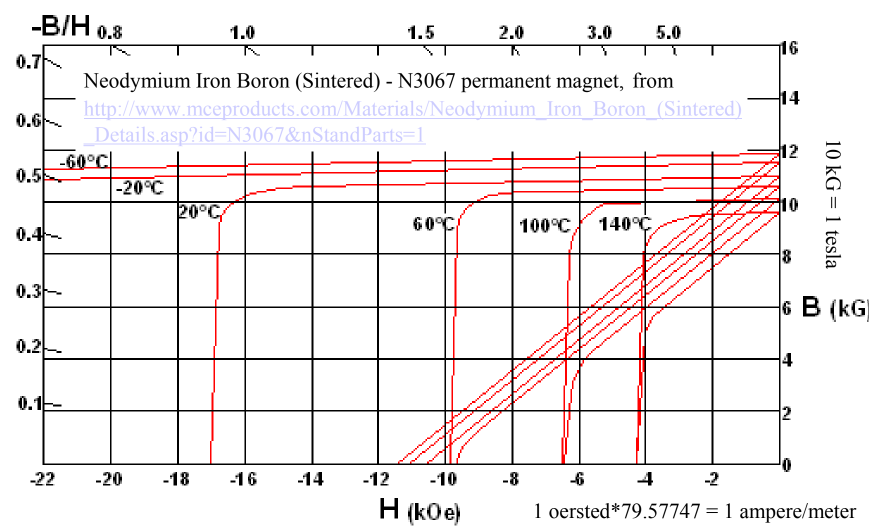
From D. Halliday & R. Resnick, *Physics Parts I & II Combined 3rd edition*

  - Magnet geometry affects this calculation (A LOT! See http://www.mceproducts.com/)





From the 2.007 kit: Permanent magnet with steel pole piece



Magnetic Circuits: *Applications*

- Magnets can be used for lifting objects:
  - Permanent magnets will attract an object, but how do you get them to let go?
  - Electromagnets are easy to design and use, and can let go of objects
- Magnets can be used as wheels on metal surfaces:
  - First used for the 1999 2.007 contest Ballcano
  - See http://pergatory.mit.edu/magnebots/

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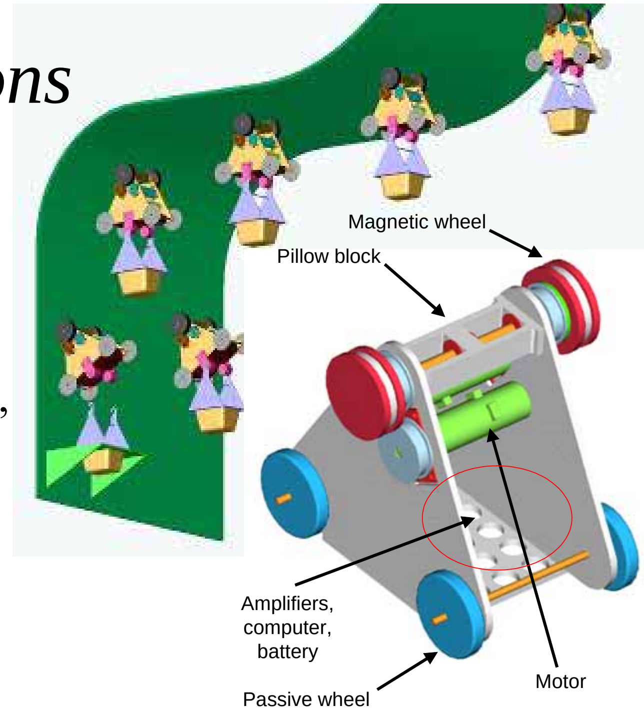
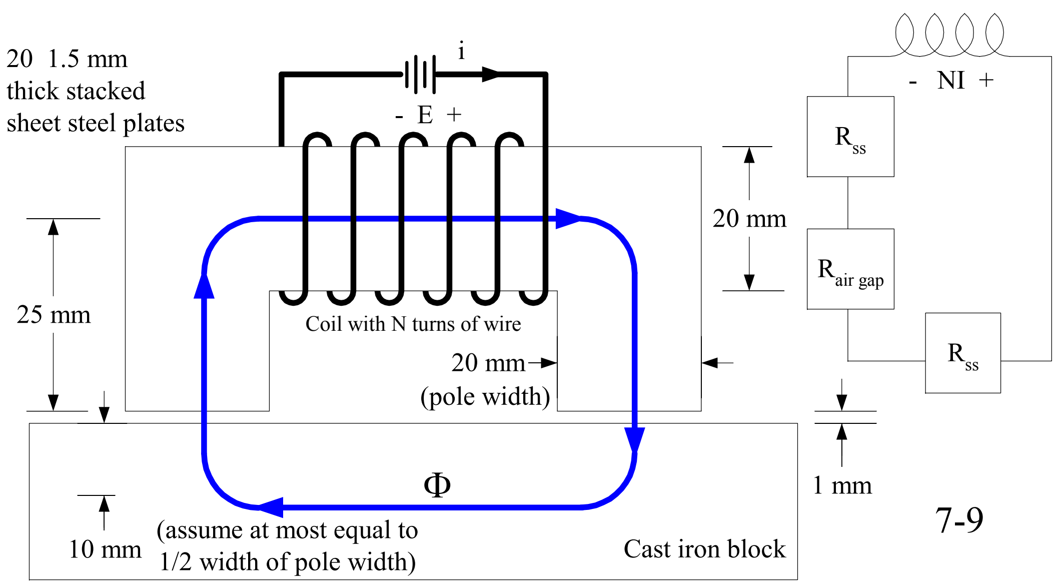
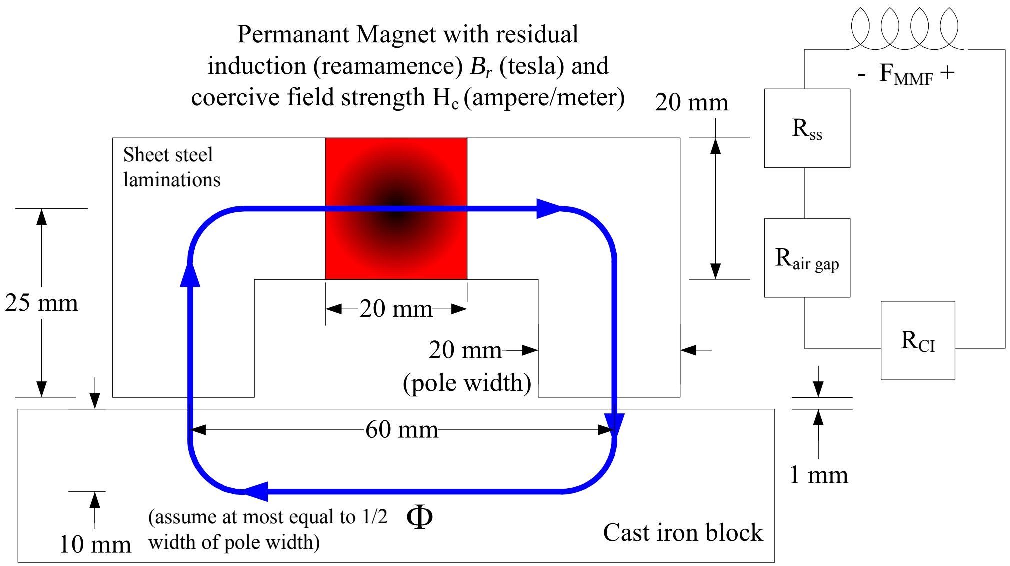




Magnetic Circuits:
Permanent Magnet Attraction

- Permanent magnets can be used to provide all or most of the lifting force in a system
- To turn off the force, a "shunt" can be moved into place to provide a low reluctance path for the flux so it does not permeate through the air gap.

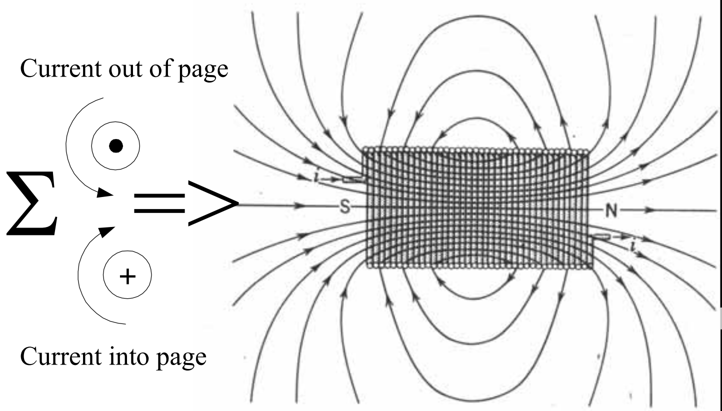


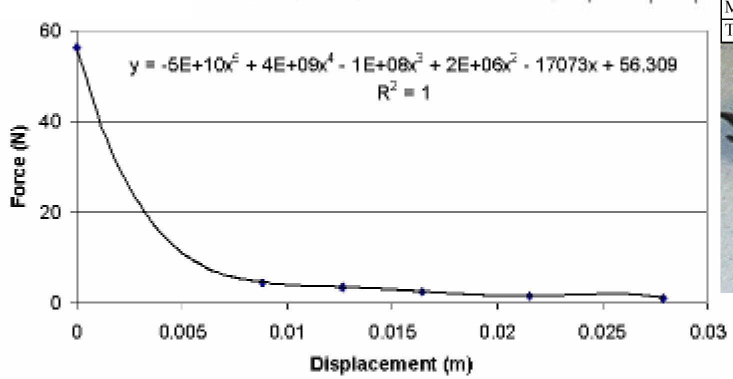
Lifting_permananet_magnet.xls	
By Alex Slocum, Last modified 10/5/04 by Alex Slocum	
Enters numbers in **BOLD,** Results in **RED**	
Mass of object to lift, M (kg)	**0.5**
Force required to lift object, F (N)	**4.9**
Results	
Total circuit reluctance, Rtotal	**60808361.9**
Total magnetic flux in the circuit, phi	**2.62E-04**
Maximum attractive force, Fmax (N)	**22.7**
Effective magnetic "pressure" (atm)	**0.2**
Safety Factor	**4.6**
Magnet	
Strength of magnet, Bmagnet (tesla)	**1.00**
Length of Magnet, Lmag (mm)	**20**
Width, wmag (mm)	**20**
Depth (into page) dmag (mm)	**30**
Magnetic circuit path area, Amag (mm^2)	**600**
Reluctance (resistance), Rmag	**59683103.7**
Magnetomagnetic force, Fmmf_magnet (At)	**15915**
Flux Focussing Metal (values per side unless noted)	**Sheet steel**
Magnetic circuit path length, L_1 (mm)	**45**
Width (at pole), w_1 (mm)	**20**
Depth (into page) d_1 (mm)	**30**
Magnetic circuit path area, A_1 (mm^2)	**600**
Flux density (assume equal to magnet), B_1 (Tesla)	**1.00**
From B-H curve, magnetic field intensity, H_1 (At/m)	**400**
Reluctance per side	**30000**
Total flux focussing metal reluctance, Rss	**60000**
Air gap (assume 2 sides equal, values per side unless noted)	
Air gap, Lag1 (mm)	**0.1**
Air gap reluctance	**132629**
Total air gap reluctance, Rair_gap	**265258**
Object being lifted	**cast iron**
Magnetic circuit path length, Lobl (mm)	**80**
Width, wobl (mm)	**20**
Depth (into page) dobl (mm)	**30**
Magnetic circuit path area, Aobl (mm^2)	**600**
Flux density (assume equal to magnet), Bobl (Tesla)	**1.00**
From B-H curve, magnetic field intensity @Breq, Hobl (At/m)	**6000**
Reluctance (resistance), Robl	**800000**
Permeativity of free space, mu0 (H/m)	**1.26E-06**

Magnetic Circuits: *Solenoids*

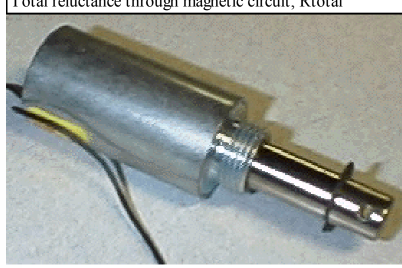
- Solenoids use a coil to generate a magnetic field that then attracts an iron plunger
  - They have limited pull force and stroke and are often used to open or close devices
    - Understanding their physics of operation helps to ensure that you will not improperly use them
    - Motion of the plunger into the case reduces the potential energy and hence creates a force
    - The force drops off rapidly (nonlinearly) with motion of the plunger
  - The force/displacement curves can be predicted, but typically just use curves from the manufacturer (e.g., www.ledex.com)

From D. Halliday & R. Resnick, *Physics Parts I & II Combined 3rd edition*

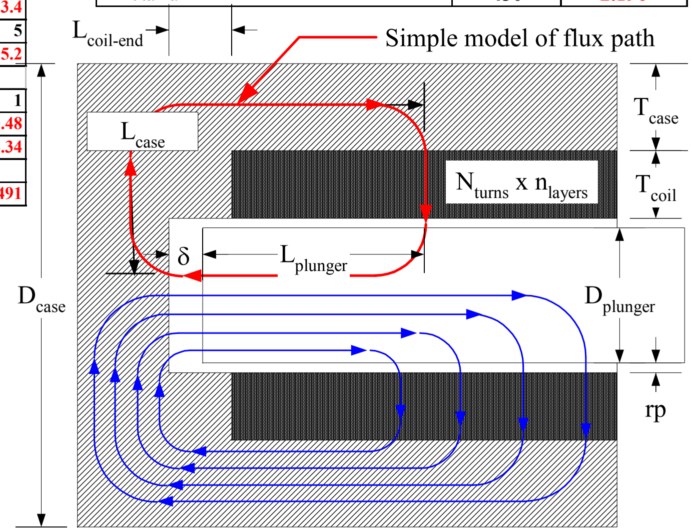


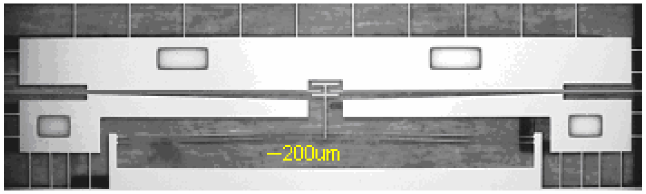


Solenoid_force.xls	
To estimate pulling force of a solenoid plunger	
By Alex Slocum & Jeff Lang	
Last modified 6/22/03 by Alex Slocum	
Enters numbers in **BOLD**, Results in **RED**	
Coil	
Current, i (amps)	**2**
Number of turns, Nturns	**200**
number of layers, nlayers	**1**
Magnetomotive force, Fmcoil (ampere-turns)	400
wire diameter, dwire (mm)	**0.25**
Length of coil, Lcoil (mm)	50
Total length of wire, Lwire (mm)	9708
Coil material (assumed copper, see below) resistance μΩmm	17
Wire resistance, Rwire (Ohms Ω)	3.36
Power dissipated as heat (Watts)	13.4
Distance coil end to case bottom (>delta max), Lcoil_end, (mm)	**5**
Inside diameter, Dcoil (mm)	15.2
Plunger	
Plunger axial displacement, delta (mm)	**1**
Magnetic flux density across plunger end gap, Bgap (tesla)	0.48
Resulting force F (N)	16.34
Magnetic circuit path elements:	
Total reluctance through magnetic circuit, Rtotal	4695491



Wire_resistivity.xls		
To estimate resistance of a length of solid wire		
By Alex Slocum & Jeff Lang		
Last modified 6/22/03 by Alex Slocum		
Enters numbers in **BOLD**, Results in **RED**		
wire diameter, D (mm)	**0.5**	
wire length, L (mm)	**1000**	
Resistivity:	μΩ-mm	R (Ohms)
gold	**24**	0.122
aluminum	**27**	0.138
copper	**17**	0.087
silver	**16**	0.081
tungsten	**56**	0.285
titanium	**430**	2.190



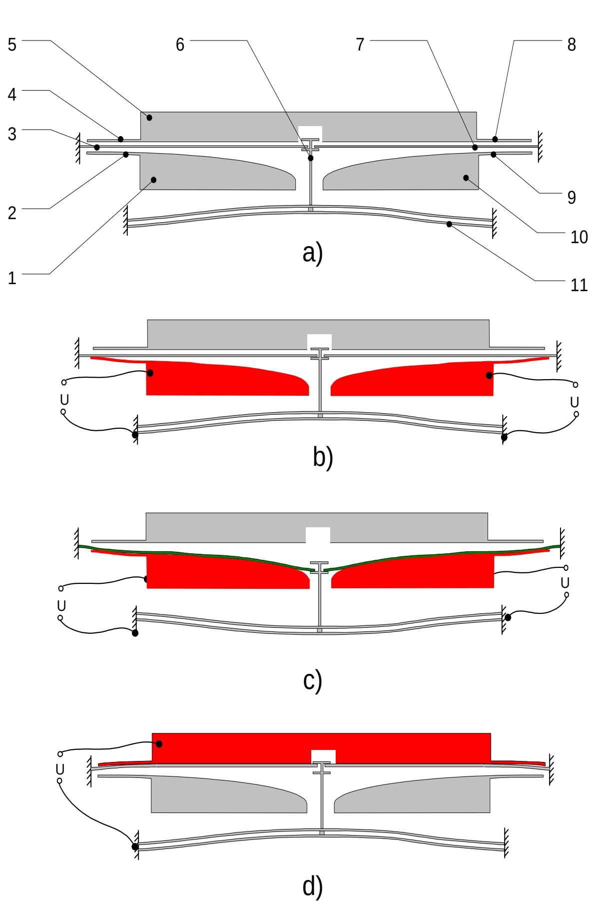


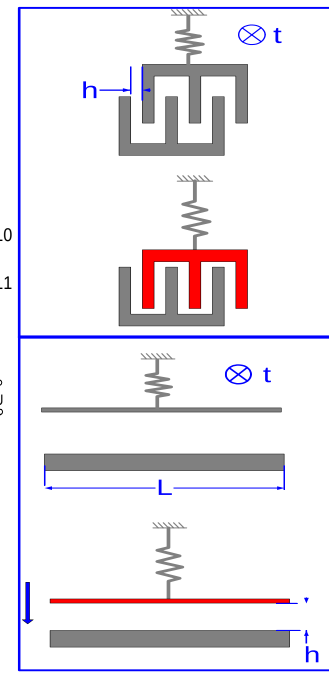
Lorentz Forces

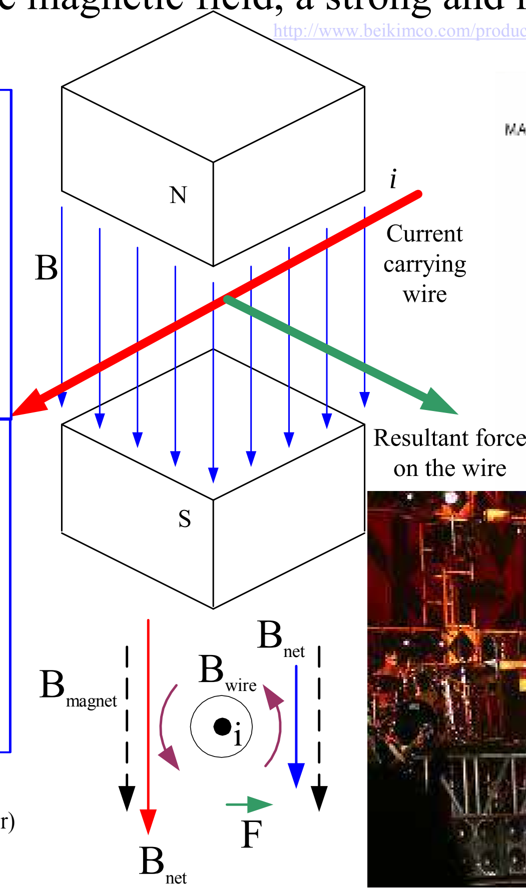
Hendrick Antoon Lorentz
(1853-1928)

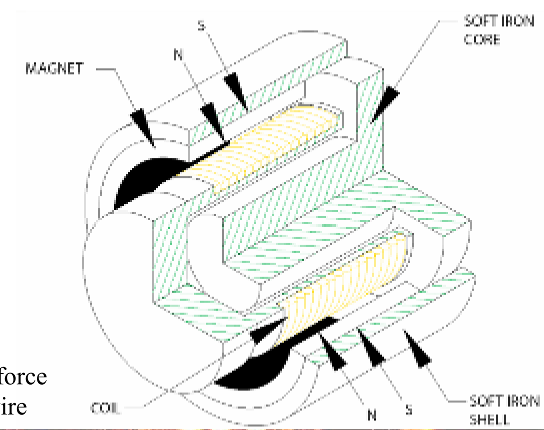
- Lorentz forces are created either from differential charges between objects (from Coulomb's law) or by a coil in a permanent magnet field
  - With a uniform magnetic field over a wide region, a reasonably constant force can be generated in a current carrying wire that moves within the field
    - As long as the wire stays totally in the magnetic field, a strong and linear bi-directional force is created

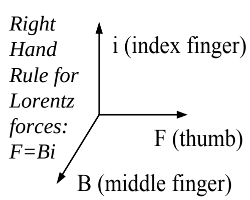
From BEI KImco's website:
http://www.beikimco.com/products/actuator/guide/BEIKimco-VCA-AppGuide2002.pdf#Theory



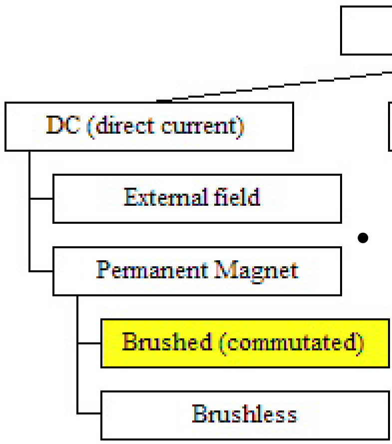








The POWER of Lorentz force actuators unleashed!
(from Wango Tango - Rose Bowl, Pasadena, CA, May 17, 2003 Photo by Jay Gilbert http://www.kissonline.com/news/index.php?page=news_index.html)



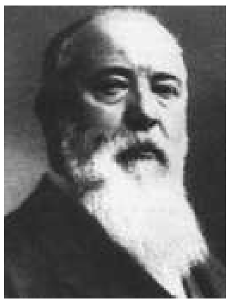
Electric Motors

Werner von Siemens
(1816-1892)

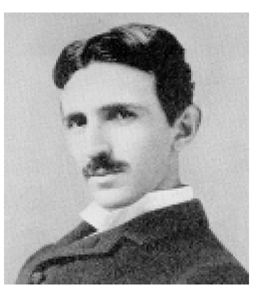
- Electric motors convert *voltage* into *speed* and *current* into *torque:*

  $\omega = K_b * V$ $\Gamma = K_T * I$ $K_b = K_T$ (mks units)

  - Different types of motors have different torque-speed responses
  - Remember, *power* is the product of *torque* Γ and *speed* ω: Watts=N-m*rad/sec
- High current creates heat in the motor
  - Power dissipated in the motor windings is equal to the product of the current squared and the winding electrical resistance R: $P_{thermal} = I^2R$
  - Total electrical power = current X voltage, because some power is also dissipated in the magnetic circuit
  - It is often more efficient to get high torque/low speed from a high speed motor coupled to a gearbox
- *DC brushed motors* commonly use carbon brushes to provide current to coils on the rotor to create electric fields perpendicular to the magnetic field
  - Linear torque-speed response and are commonly used in robot design contests

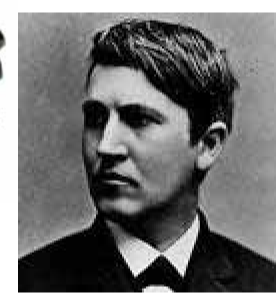


Zenobe Gramme
(1826-1901)



Nikola Tesla
(1856-1943)

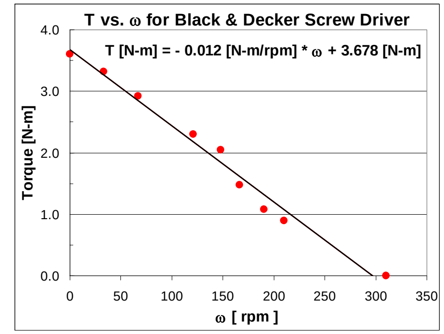
George Westinghouse
(1846-1914)



Thomas Edison
(1847-1931)

Charles Steinmetz
(1865-1923)

Electric Motors: DC *Brushed Motors*



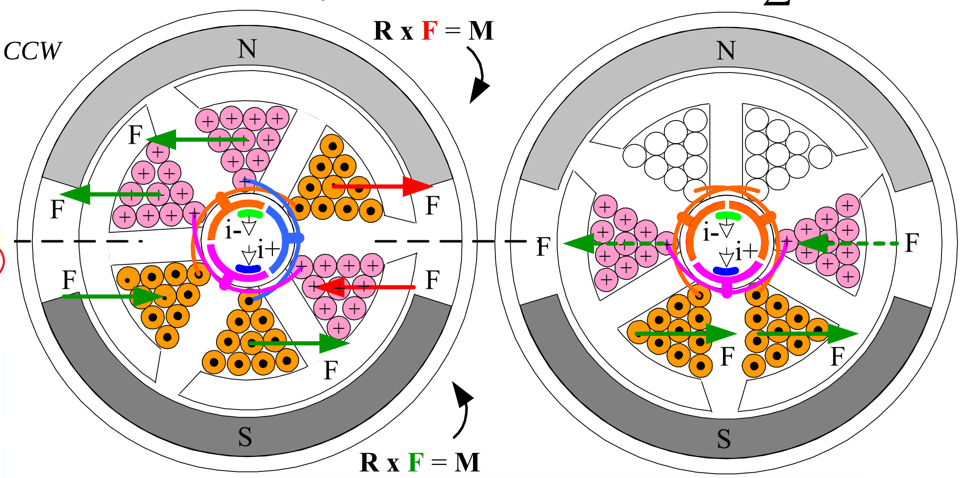
- For a DC motor with a linear torque-velocity relationship, maximum power is obtained when the motor runs at ½ maximum speed:

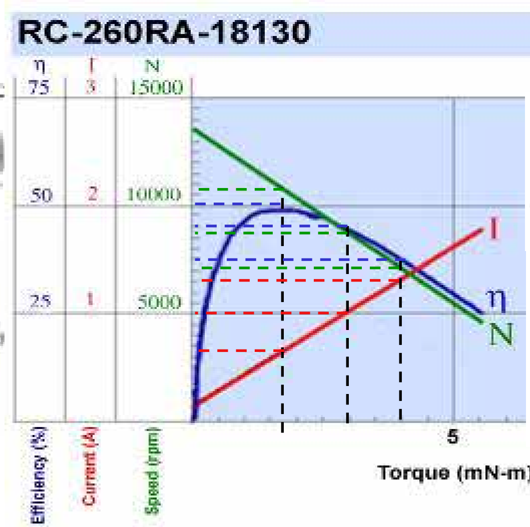
$$\Gamma = S\omega + \Gamma_{\max} \qquad S = {-\Gamma_{\max}}/{\omega_{\max}}$$

$$P = \Gamma\omega = S\omega^2 + \Gamma_{\max}\omega$$

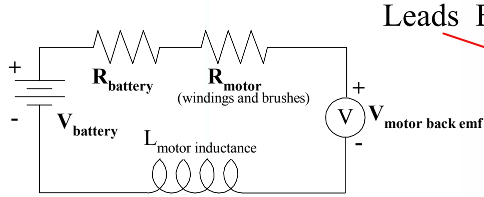
$$\frac{\partial P}{\partial \omega} = 0 = 2S\omega + \Gamma_{\max} \quad \Rightarrow \omega = \frac{\omega_{\max}}{2}$$

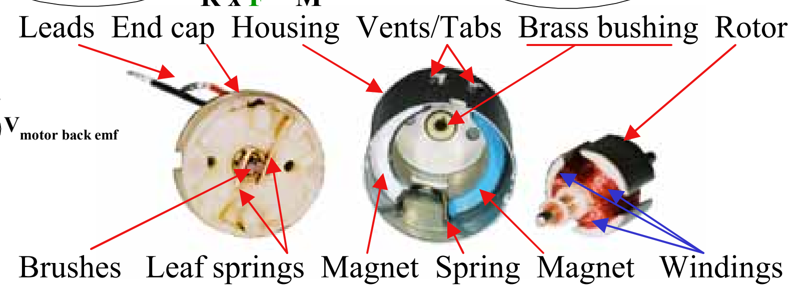
Current out of the page creates a CCW magnetic field (right hand rule), which distorts the motor's permanant magnet field





Motor solid model





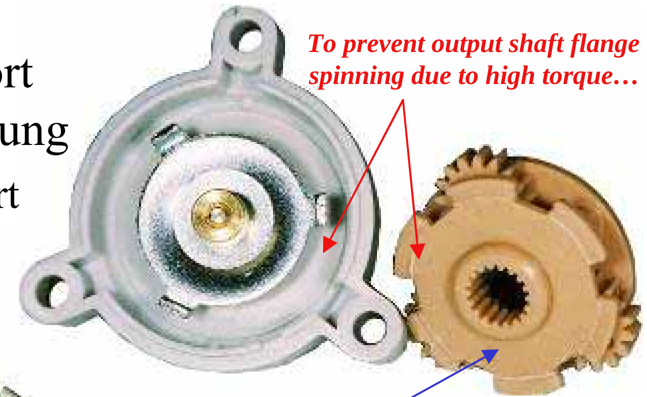
MODEL	VOLTAGE		NO LOAD		AT MAXIMUM EFFICIENCY					STALL		
	OPERATING RANGE	NOMINAL	SPEED	CURRENT	SPEED	CURRENT	TORQUE		OUTPUT	TORQUE		CURRENT
			r/min	A	r/min	A	mN·m	g·cm	W	mN·m	g·cm	A
RC-260RA-18130	4.5 ~ 6.0	4.5V CONSTANT	9800	0.14	7750	0.53	1.48	15.1	1.20	7.06	72	2.00
		6V CONSTANT	13600	0.17	10840	0.67	1.71	17.5	1.94	8.44	86	2.62

Resistance across motor leads 3-5 Ω new, 1-3 Ω after wear-in!

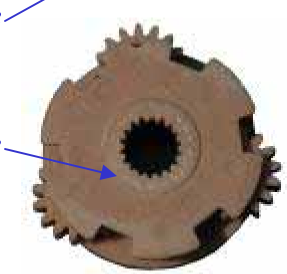
DC Brushed Motors: *Gearmotors*

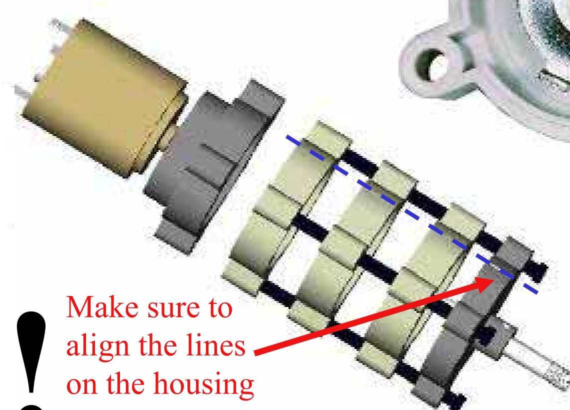
- Integrating the transmission with the motor saves space and the need for a coupling
  - Wormgear drives are used to power electric automobile seats and windshield wipers (see page 6-23)
    - High transmission ratio, single stage, not back-driveable
  - Planetary transmissions are often back-driveable (see page 6-15)
- Output shafts and their support bearings will generally support small robot machine radial loads if they are not too far overhung
  - In general, be extremely careful when using output shaft support bearings to support radial loads!

To prevent output shaft flange spinning due to high torque…

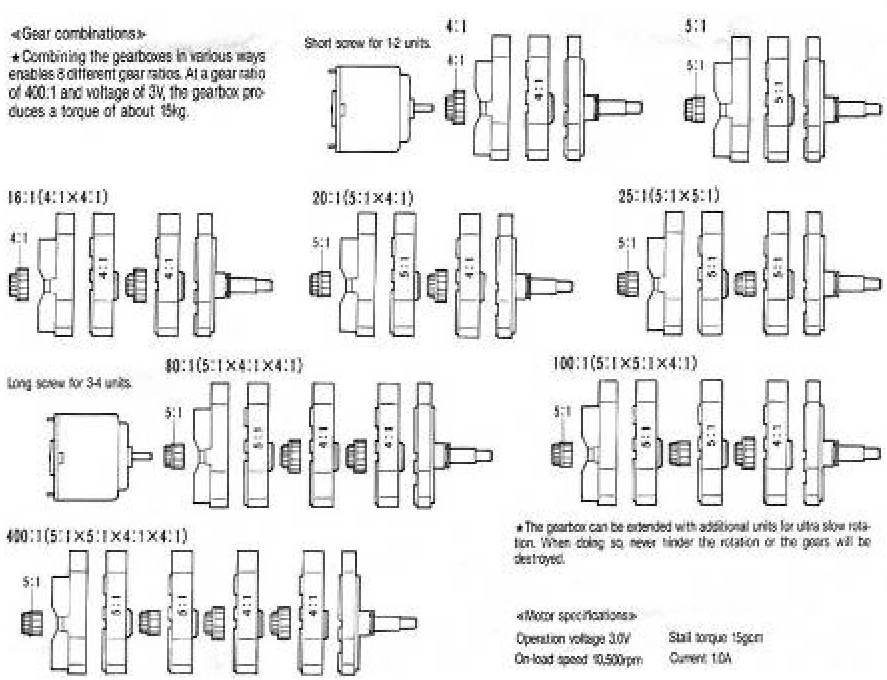


Sand or file the final stage's inner hub to be flush with the disk! Then use two washers on the inside…

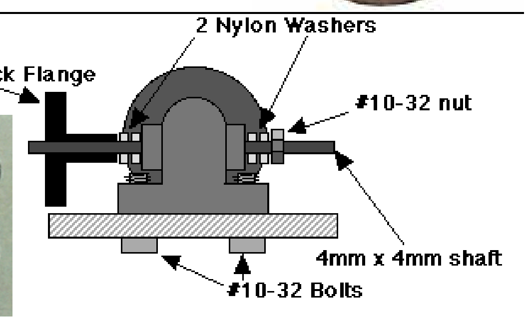




! Make sure to align the lines on the housing stages



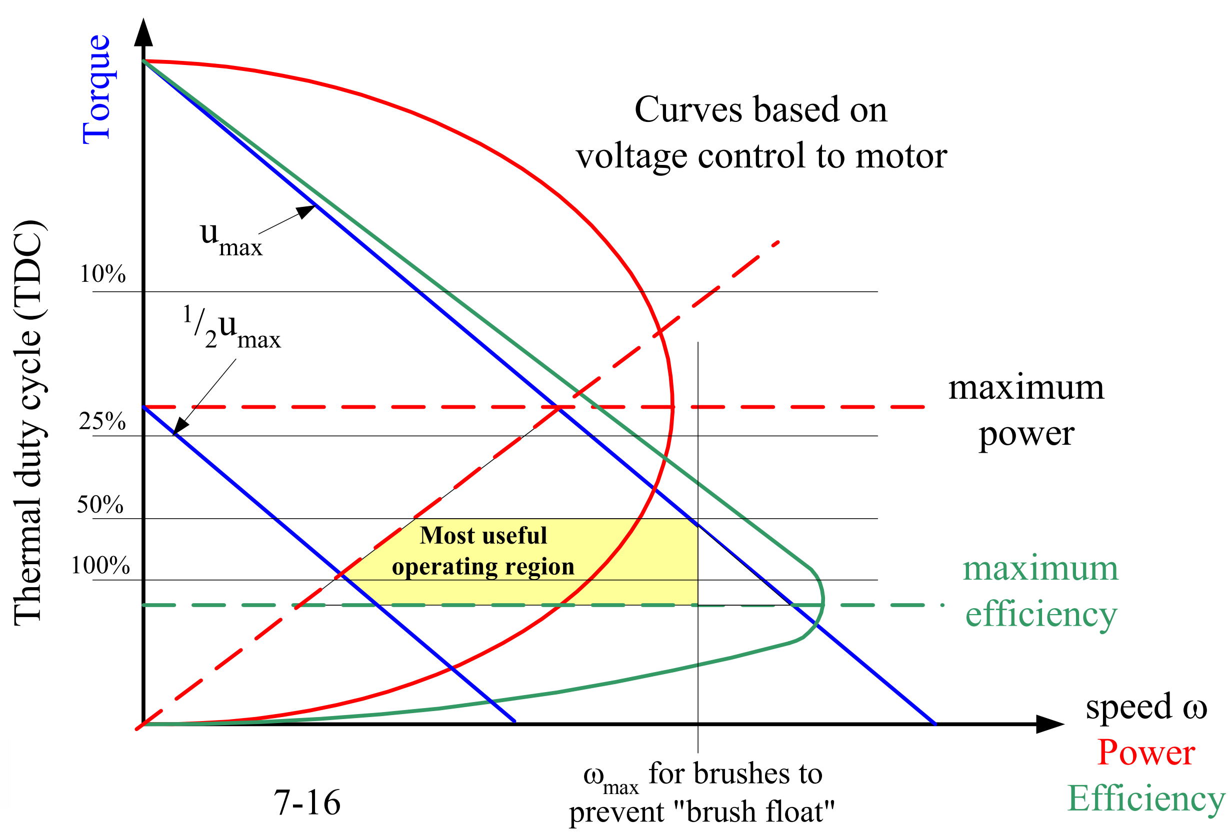
Bosch automotive power seat control motor-wormgear



DC Brushed Motors: *Best Operating Region*

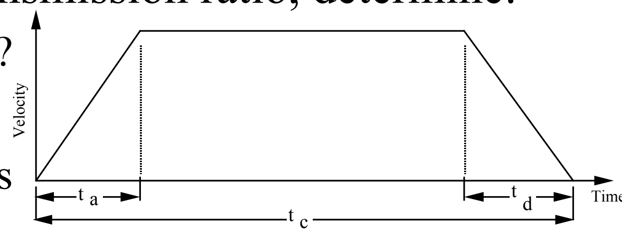
- When selecting a motor and transmission, the motor must not be too big nor too small:
  - The maximum operating voltage u_{max} (and hence maximum current) is set to prevent motor magnet demagnetization
    - To continually use a motor at less than ½ u_{max} is not cost effective
- ***HEAT*** (thermal overload) is the greatest cause of motor damage
  - Time must be allowed between on-cycles for the motor to cool down

Motor mass: 26 grams
Rotor mass: 10 grams
Rotor inertia: 560 g-mm^2

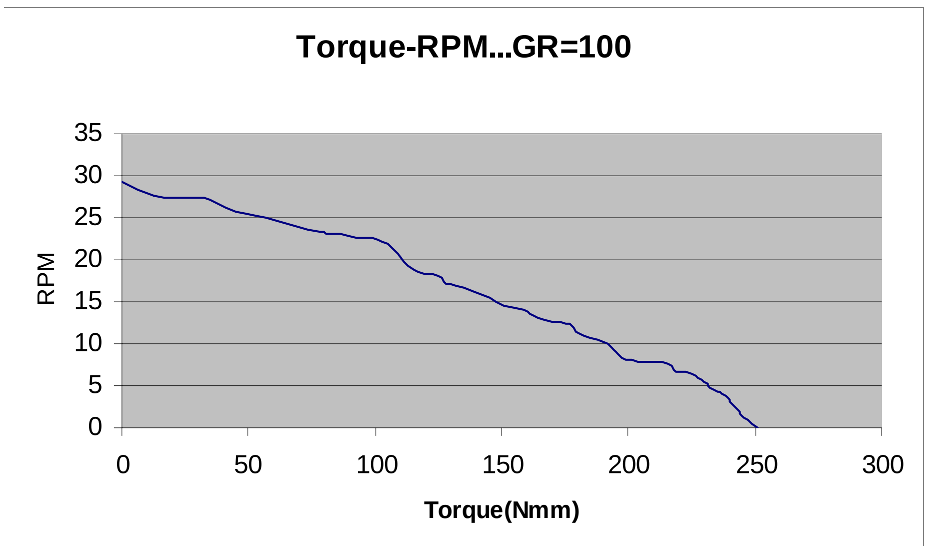


DC Brushed Motors: *Design Spreadsheets*

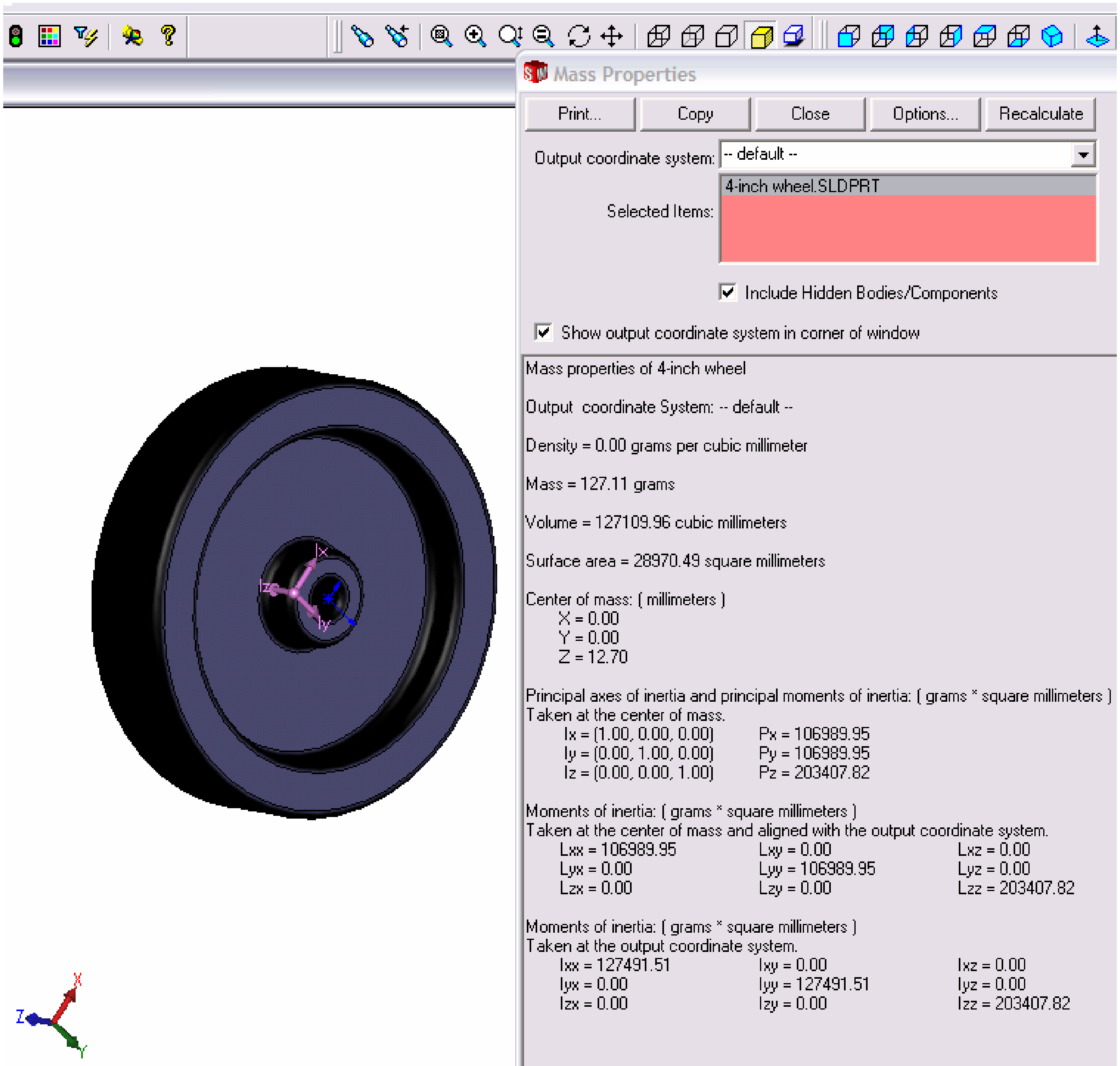
- Use the *Matched Inertia Doctrine* to find the "optimal" transmission ratio
- Motor power rate should be > load power rate
- With an obtainable transmission ratio, determine:
  - Will the wheels slip?
  - Move times
  - Battery requirements



- Play "what-if" scenarios with the spreadsheet *Gearmotor_move.xls*

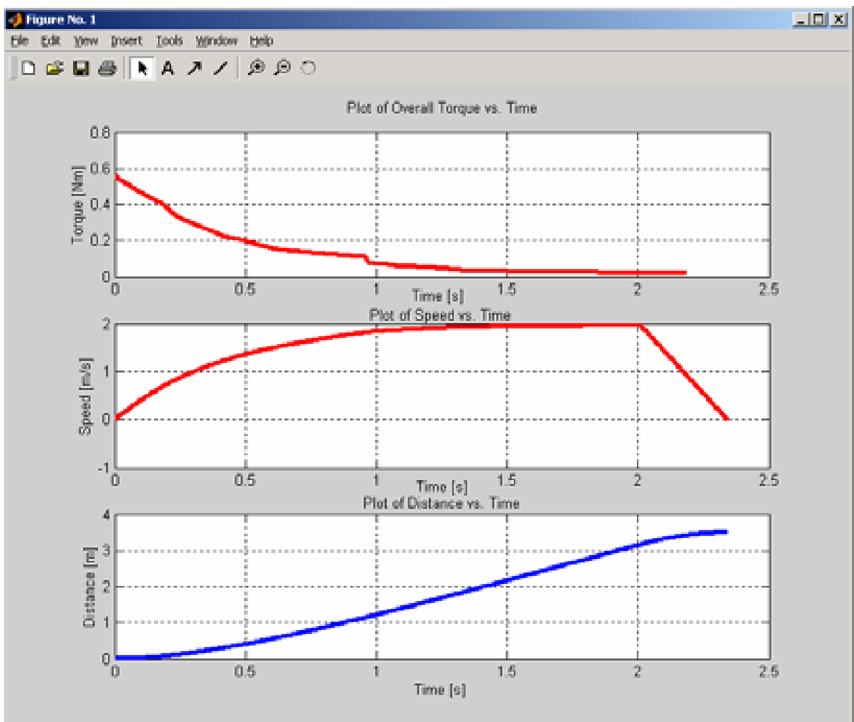


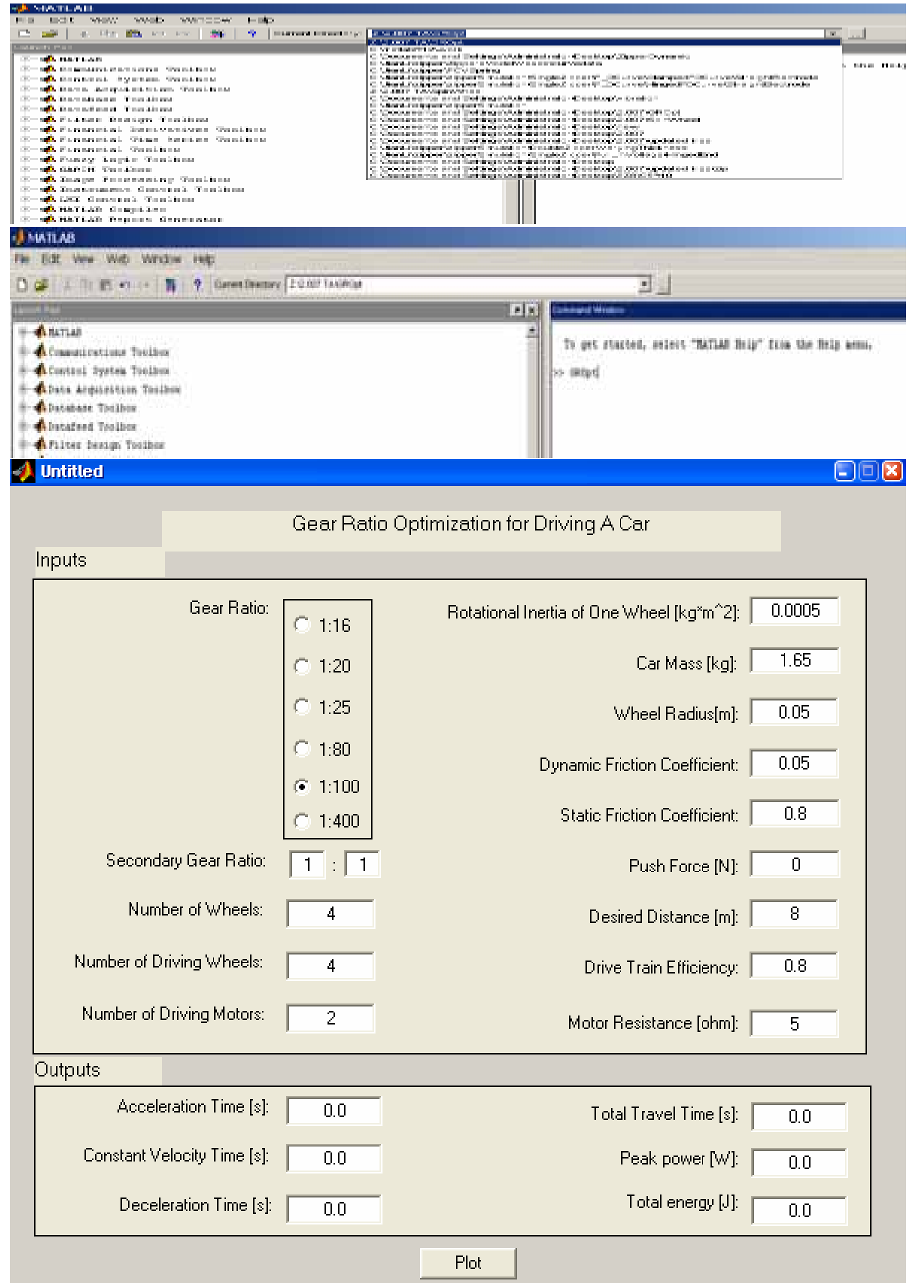
Gearmotor_move.xls		
To estimate inertia of gearmotor and find system optimal transmission ratio		
By Alex Slocum		
Last modified 8/22/03 by Alex Slocum		
Enters numbers in **BOLD,** Results in **RED**		
Motor (torque and speed are NOT at absolute max values, but rather at max efficiency)		
Rotor mass, Mr (grams, kg)	**10**	0.0100
Diameter, Dm (mm, m)	**15**	0.0150
Mength, Lm (inches, m)	**12**	0.0120
Number of drive motors, Nm	**2**	
Nm Motors' rotary inertia, Jmotor (kg-m^2, g-mm^2)	5.63E-07	563
Motor operating efficiency, etamotor	50%	
Max motor torque, gammax (m-N-m, N-m)	**8**	0.008
Max motor speed, wmax (rpm, rad/s)	**13500**	1414
Motor speed at maximum efficiency, wmaxeff (rpm, rad/s)	**11500**	1204
Steepness S (N-m-s/rad)	5.659E-06	
Planetary Transmission		
Planet carrier assembly mass Mplanet, (grams, kg)	**2.1**	0.0021
Planet carrier outer diameter, Dpod (mm, m)	**20**	0.0200
Planet carrier inner diameter, Dpid (mm, m)	**10**	0.0100
Number of stages, Nstage	**3**	
Efficiency per stage, etastage	**90%**	
Planetary total rotary inertia, Jplanets (kg-m^2)	3.94E-07	
Output shaft mass, Mouts (grams, kg)	**4**	0.0040
Output shaft diameter, Douts	**4**	0.0040
Output shaft rotary inertia, Jouts (kg-m^2)	8E-09	
Total Nm planetary transmissions' rotary uinertia, Jtrans (kg-m^2)	8.04E-07	
Transmisssion efficiency (includes car wheels), etatrans	66%	
Car		
Mass of car, Mcar (kg)	**4**	
Diamter of wheel, Dwheel (mm, m)	**75**	0.0750
Max car acceleration, acar (m/s^2, g)	0.98	0.10
External loads, friction... Fext (N)	**0**	
2Wd or 4WD, Nwd	**2**	
Coefficient of friction wheel-to-ground, mu	**0.2**	
Optimal Transmission ratio by Matched Inertia Doctrine		
Optimal transmission ratio, ntrans	64	
Confirm: Number of stages = # required to achieve desired ntrans	yes	
Actual transmission ratio to be used, ntranactual	**64**	
Actual equivelent linear inertia of motor and tranny, mtrans (kg)	4.0	
Total actual sysetm equivelent inertia, Mtotal (kg)	8.0	
Power rates		
Motors' total power rate, PRmotor	187.41	
Load power rate, PRload	3.86	
System goodness (should be >1): PRmotor/(4PRload/etatrans)	7.96	
Motion Results		
Start-to-stop travel distance (must be>Xaccel), Xdes (m)	**1.5**	
Max. potential tractive effort (even mass distribution), Ftraction (N)	3.92	
Max. motor tractive effort (even mass distribution), Ftractive (N)	17.92	
Can wheels slip?	yes	
Maximum theoretical car speed vmaxpot (m/s)	0.83	
Car speed at max motor η, vmaxeff (m/s)	0.71	
"Steepness", slinear (N-s/m)	-4.73	
Time to accelerate to speed at max motor η, taccel (seconds)	3.22	
Taylor series approx. time to accelerate to speed at max motor η	3.89	
Distance travelled during acceleration to max speed, Xaccel (m)	1.48	
Time to travel 1/2 desired travel distance, tohtd (seconds)	1.75	
Total travel time, ttotal (seconds)	3.49	
Approx. travel time (no velocity limit, Taylor series approximation)	3.49	
Battery Requirements		
Estimated maximum power draw from batteries, Pbat (W)	8.43	
Estimated maximum energy draw from batteries, Ebat (J=N-m)	29.5	


Mass Properties
Print...
Copy
Close
Options...
Recalculate
Output coordinate system:
-- default --
Selected Items:
4-inch wheel.SLDPRT
Include Hidden Bodies/Components
Show output coordinate system in corner of window
Mass properties of 4-inch wheel
Output coordinate System: -- default --
Density = 0.00 grams per cubic millimeter
Mass = 127.11 grams
Volume = 127109.96 cubic millimeters
Surface area = 28970.49 square millimeters
Center of mass: (millimeters)
X = 0.00
Y = 0.00
Z = 12.70
Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.
Ix = (1.00, 0.00, 0.00) Px = 106989.95
Iy = (0.00, 1.00, 0.00) Py = 106989.95
Iz = (0.00, 0.00, 1.00) Pz = 203407.82
Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.
Lxx = 106989.95 Lxy = 0.00 Lxz = 0.00
Lyx = 0.00 Lyy = 106989.95 Lyz = 0.00
Lzx = 0.00 Lzy = 0.00 Lzz = 203407.82
Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.
Ixx = 127491.51 Ixy = 0.00 Ixz = 0.00
Iyx = 0.00 Iyy = 127491.51 Iyz = 0.00
Izx = 0.00 Izy = 0.00 Izz = 203407.82

DC Brushed Motors: *Motion Simulations*

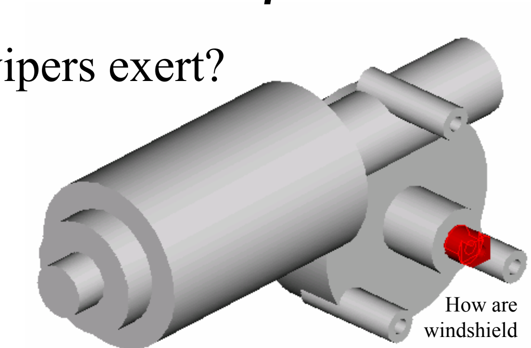
- Code written in Matlab™ enables the design engineer to integrate equations of motion step-by-step and incorporate special conditions and nonlinearities
  - This is most appropriate for the detailed design phase, particularly for critical components or systems, or high-volume products
- If sensor feedback is used for closed-loop control, motion simulations are indispensable





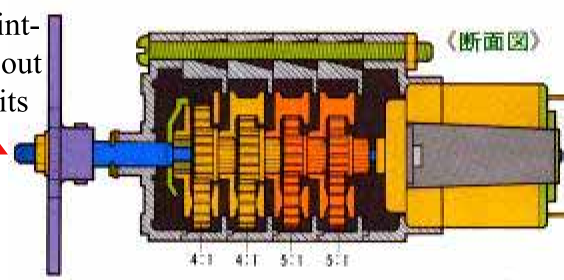
Gearmotors: *Shaft Loading & Wire Strain Relief*

- Consider a windshield wiper motor, how much of a load can the wipers exert?
  - The output shaft is 0.47” in diameter. It is a worm drive system, with the output shaft bearings about 3 shaft diameters apart.
- Consider gearmotors for robot design contests, how large of a radial load can the output shaft support?
  - Can gears be mounted such that the radial forces are nearly over the front support bearing?
  - Can gears be effectively used as a coupling…



How are windshield wiper blades attached?

What does Saint-Venant say about this shaft and its load?!

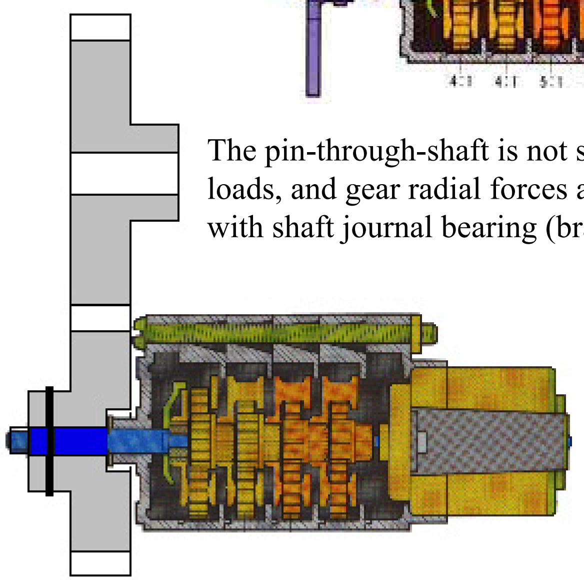


SMALL DELICATE LEADS to which THIN wires are to be soldered and then wrapped and taped to the motor to prevent external loads from being applied to the leads!

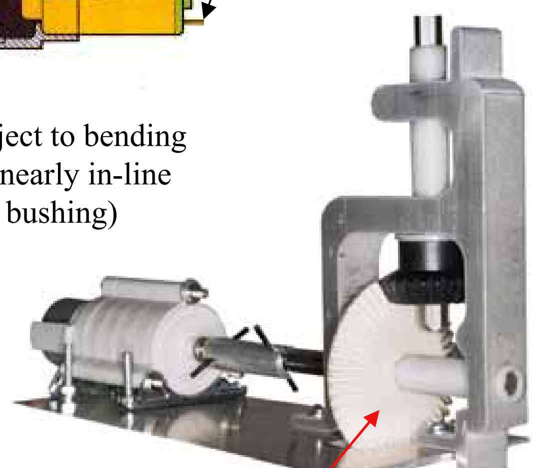
Motor as received

Wire makes a loop, and is held in place with a half-width of electrical tape

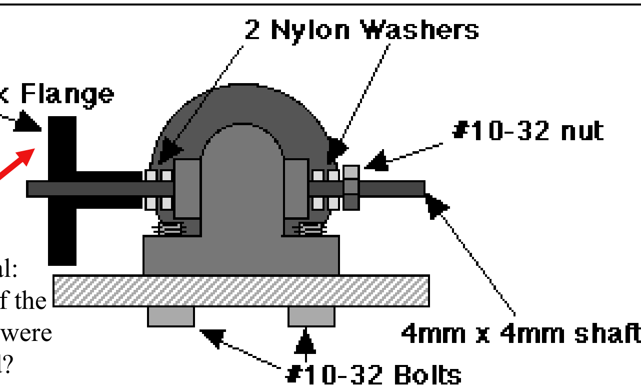
Be careful not to block cooling vents!



The pin-through-shaft is not subject to bending loads, and gear radial forces are nearly in-line with shaft journal bearing (brass bushing)

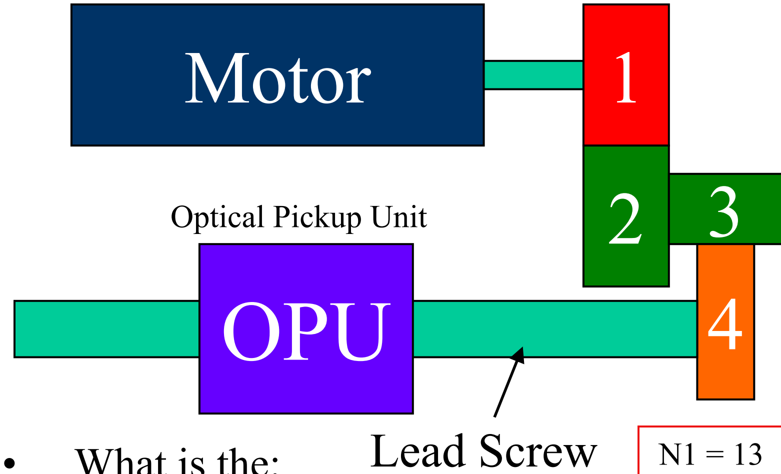


Should the big gear really be driving the little gear?



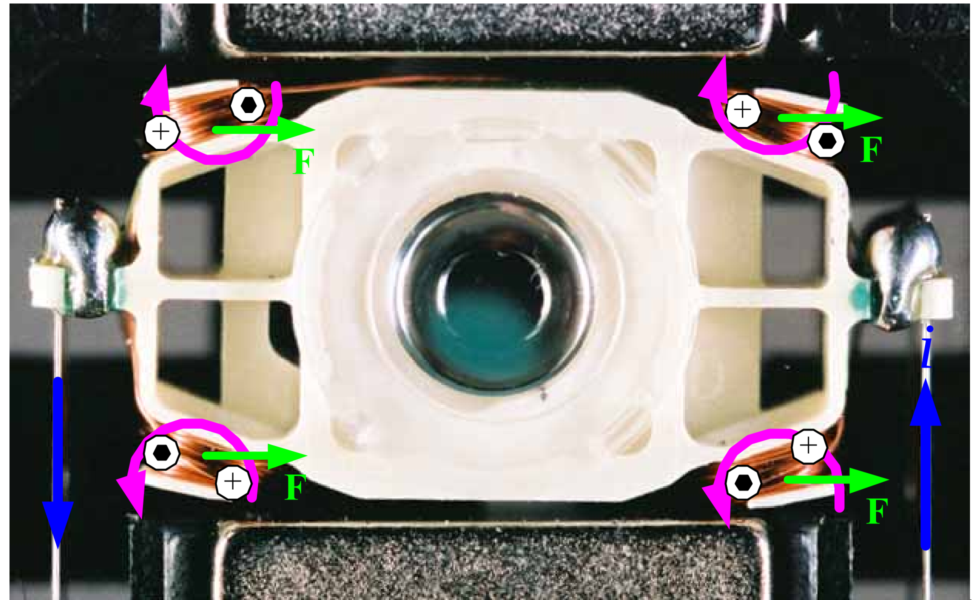
Apply reversal: What if the flange were flipped?

Case Study: A *CD Drive*

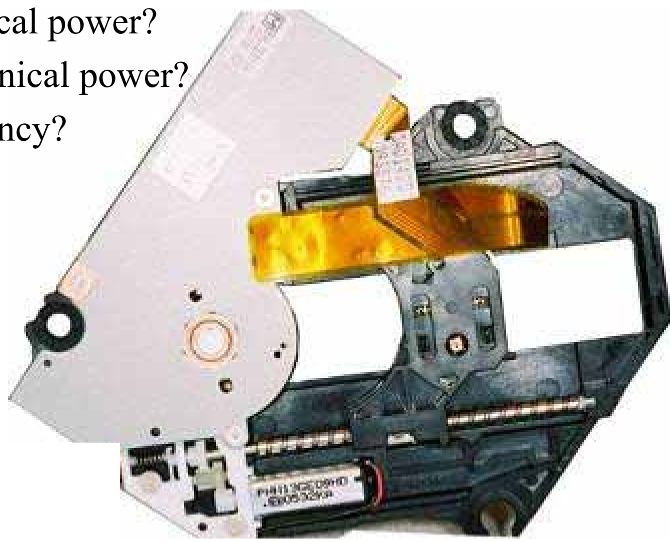


- What is the:
  - Gear Train Ratio?
  - Median output velocity?
  - Output torque at this velocity?
  - Linear speed of the OPU?
  - Force available to overcome friction?
  - Electrical power?
  - Mechanical power?
  - Efficiency?

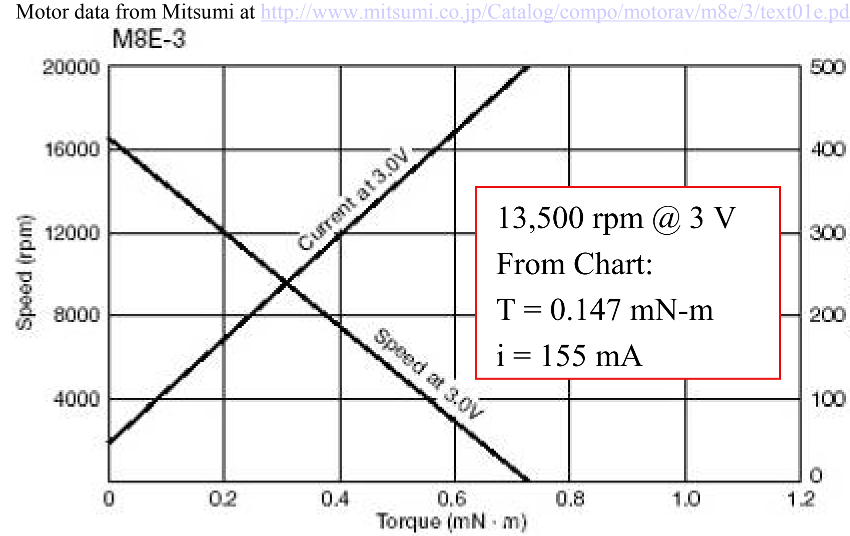
N1 = 13
N2 = 19
N3 = 12
N4 = 18
Motor rpm = 8000
Lead = 1mm/rev



Special thanks to Pat Willoughby for helping to create this case-study

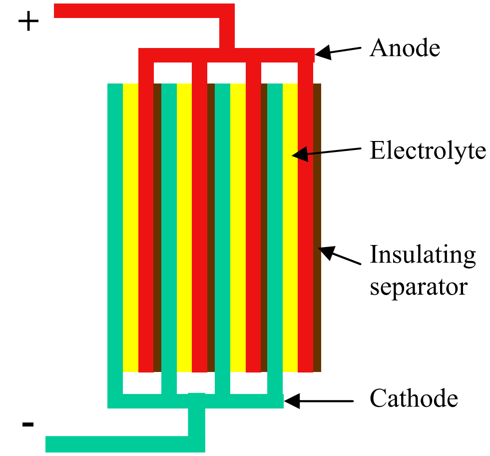


Motor data from Mitsumi at http://www.mitsumi.co.jp/Catalog/compo/motorav/m8e/3/text01e.pdf

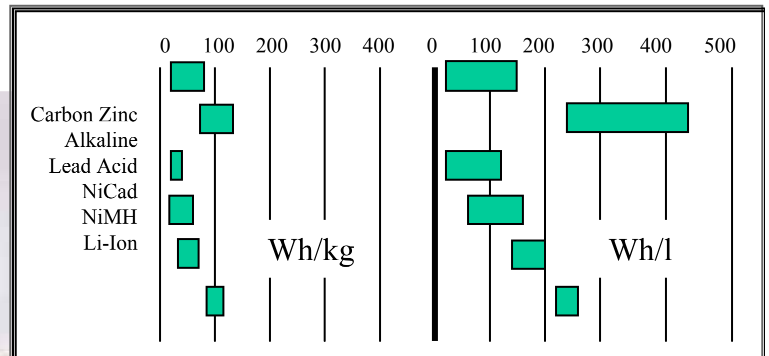


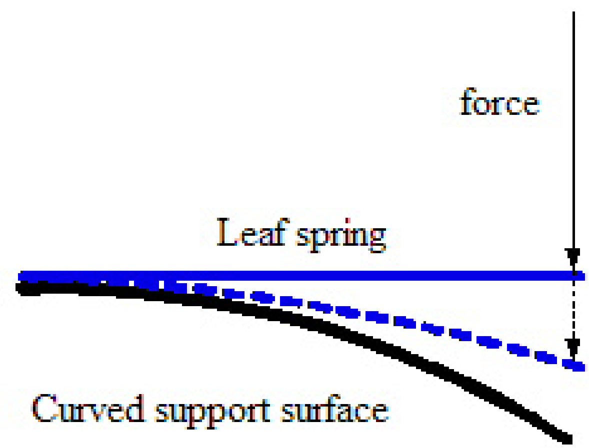
Linus Park created an awesome walker for 2.007 2000 MechaImpactAgeddon! But like all students that year, he had to deal with the **umbilical**!

Energy Supplies



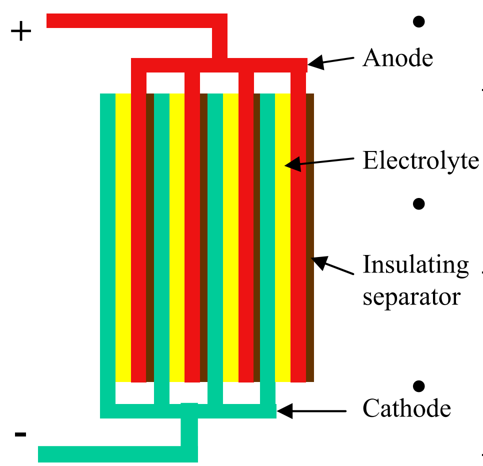
- Umbilicals
- Batteries
- Springs
- Gas cylinders
- *(Don't forget the gravity!)*



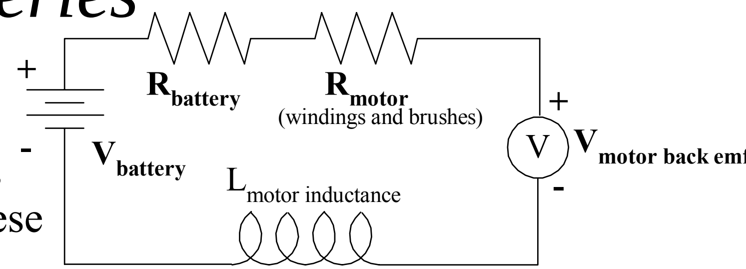


Many thanks to Mitchell Weiss for help with this battery section

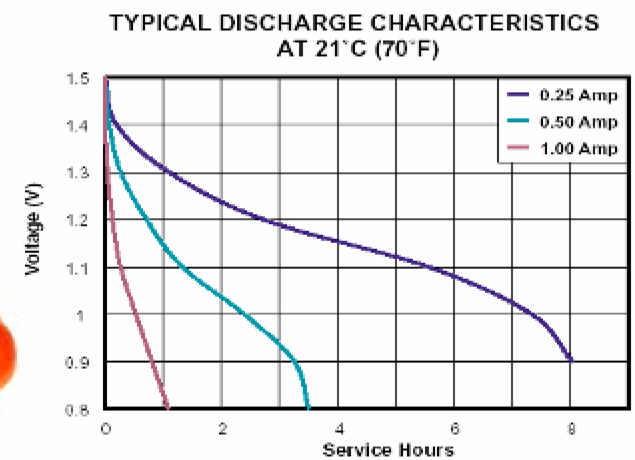
Energy Supplies: *Batteries*



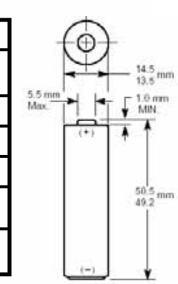
- Primary
  - Use once & dispose: Carbon-Zinc, Mercury-Oxide, Alkaline-Manganese
- Secondary
  - Rechargeable: Lead-Acid, Nickel-Cadmium, Nickel-Metal-Hydride, Lithium-Ion
- Fuel Cells
  - Consumable active material



Type	+ve	E'lyte	-ve	V	% dis	I-out
Carbon-Zinc	MnO_2	$NH_4ClZnCl_2$	Zn	1.5	10/yr	Lo
Alkaline	MnO_2	KOH	Zn	1.5	7/yr	Lo
Lead-Acid	PbO_2	H_2SO_4	Pb	2	20/mo	Med
NiCad	NiOOH	KOH	Cd	1.2	20/mo	Hi
NiMH	NiOOH	KOH	Fe	1.2	20/mo	Med



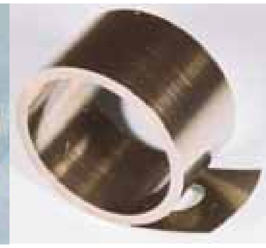
Nominal Voltage:	1.5 V
Nominal Internal Impedance:	181 m-ohm @ 1kHz
Average Weight:	23.8 gm (0.84 oz.)
Volume:	8.4 cm³ (0.51 in.³)
Terminals:	Flat
Operating Temperature Range:	-20°C to 54°C (-4°F to 130°F)
ANSI: IEC:	15A LR6



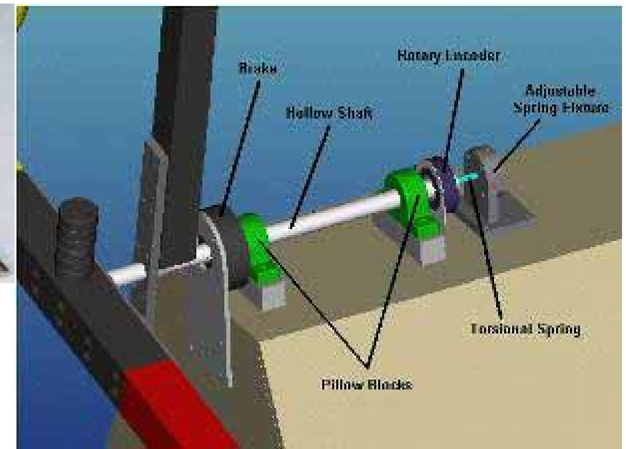
Duracell AA-MN1500 battery from http://www.duracell.com/oem/Pdf/MN1500.pdf

Alessandro Volta, (1745-1827)

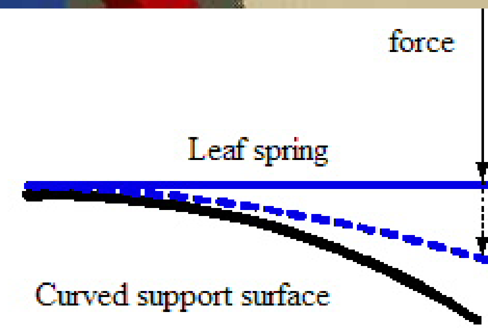
The ideal robot energy source: a cordless drill battery

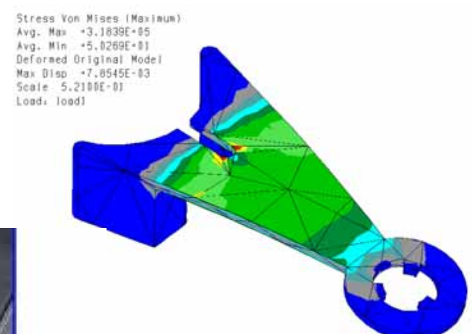


Springs

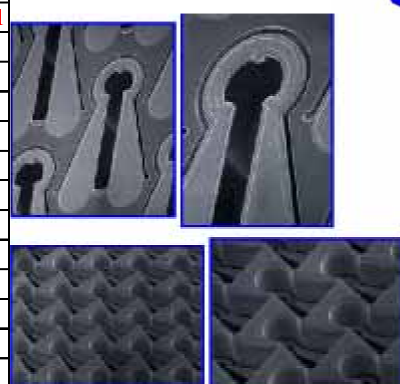


- Springs are extremely useful:
  - Small linear extension and torsional springs are often used in triggers and doors
  - The kit's constant force springs are a *serious* energy source!
- Springs are made from hard steel, and may be difficult to modify without weakening them (be careful!)
  - Use the mounting features that are integral to the spring!
- You can make your own springs with careful design of beams or torsion rods





Tapered_thickness_leaf_spring.xls		
To determine stress, deflection, & spring constant of a tapered-thickness constant-width beam		
Last modified 8/28/03 by Alex Slocum		
Enters numbers in **BOLD,** Results in **RED**		
Force, F (N, grams)	**0.5**	51
Modulus, E (N/mm^2)	**1.50E+05**	
Width, b (mm)	**0.5**	
Thickness at end, te (mm)	**0.1**	
Thickness at base, tb (mm)	**0.2**	
Length, L (mm)	**5**	
distance along beam (x=0=end), x (mm)	**0**	
Thickness slope, m	**0.02**	
constant, c_1	**9375**	
Max stress at base, maxs (N/mm^2)	**750**	
Max strain at base (%)	**1%**	
Slope (radians)	**-0.250**	
Deflection, defl (mm)	**0.681**	
Spring constant, k (N/mm)	**0.734**	
Comparative straight beam defl	**0.417**	
tapered/straight beam deflection	**1.64**	

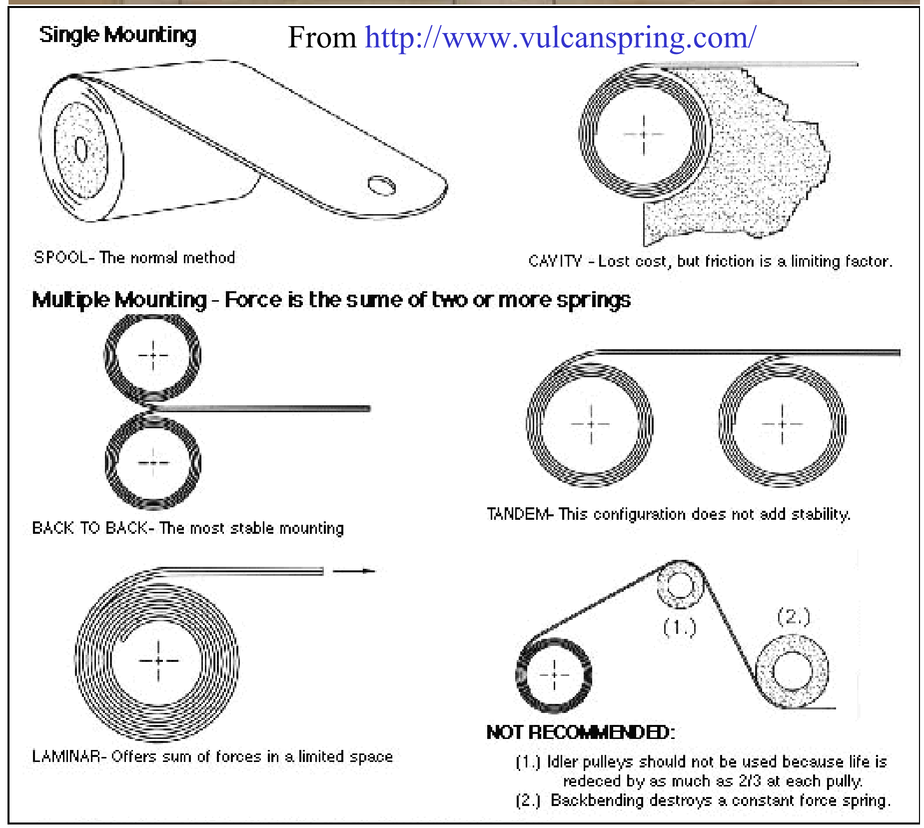


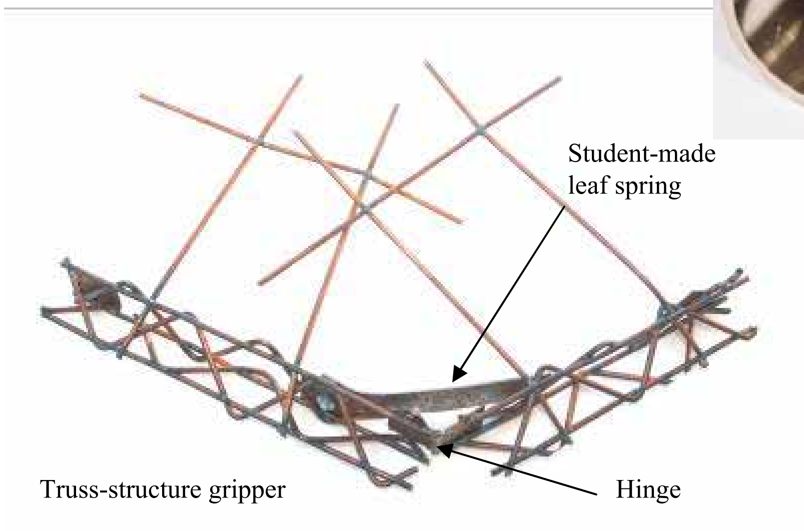
MEMS silicon microcantilevers

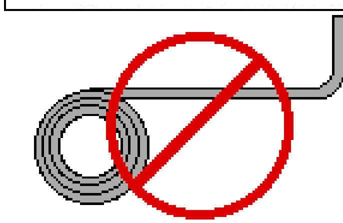
Tapered_width_leaf_spring.xls		
To determine stress, deflection, & spring constant of a constant-thickness tapered-width beam		
Last modified 8/28/03 by Alex Slocum		
Enters numbers in **BOLD,** Results in **RED**		
Force, F (N, grams)	**0.05**	5.1
Modulus, E (N/mm^2)	**1.50E+05**	
Thickness, t (mm)	**0.030**	
Length, L (mm)	**0.5**	
Width at tip, a (mm)	**0.050**	
Width at base, b (mm)	**0.200**	
resulting slope, ms	**0.300**	
I/c max, Ioc (mm^3)	**3.00E-05**	
Moment, M (N-mm)	**0.025**	
Max stress, maxs (N/mm^2)	**833**	
Max strain (%)	**0.56%**	
deflection at end, defl (mm)	**0.040**	
Spring constant, k (N/mm)	**1.263**	
Comparative straight beam defl	**0.031**	
tapered/straight beam deflection	**1.28**	

Springs: *Applications*

- The MIT 2.007 kit contains 4 constant force springs from Vulcan Spring Corp:
  - 0.75" ID, 0.475" x 0.009" thick 301 Stainless Steel, with a pull force of 2.6 lbf [11.6 N]
- Constant force springs make excellent preload devices, launchers….
  - The should be mounted ideally without modifying their structure (drilling, bending) because they could then easily break!
- ***Remember Centers of Action*** ***(page 3-24)!***



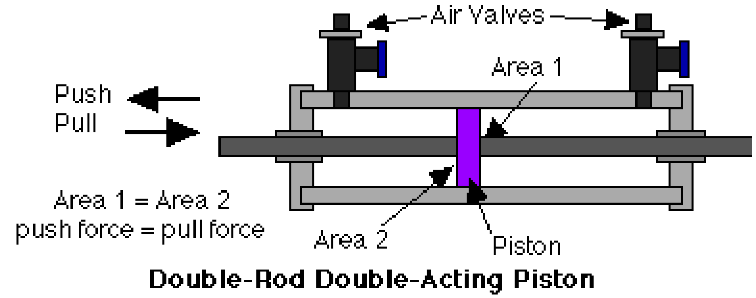




DO NOT bend spring sharper then its inner diameter.

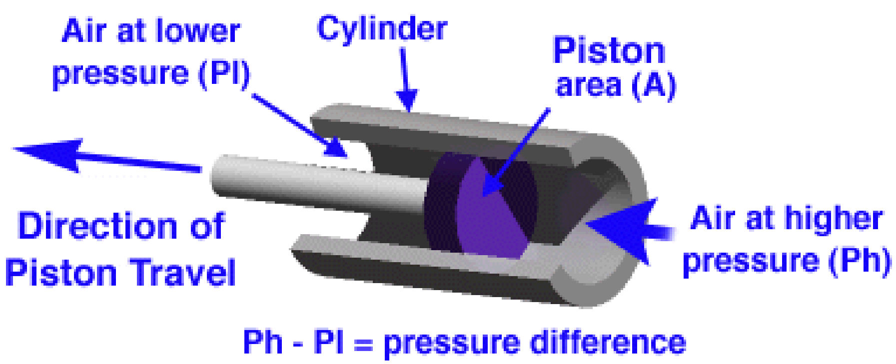
IT WILL BREAK

Pneumatic Systems



- Pneumatic (and hydraulic) cylinders let energy be piped in from a distant source
- Fluid pressure (pneumatic or hydraulic) in a cylinder acts on a movable surface (the piston) which generate a force that is then transmitted through the rod
  - Provided through an umbilical line, or from a pressurized gas bottle
  - A small solenoid valve is used to control the flow of gas
  - Incredible forces can be achieved through the use of a large area

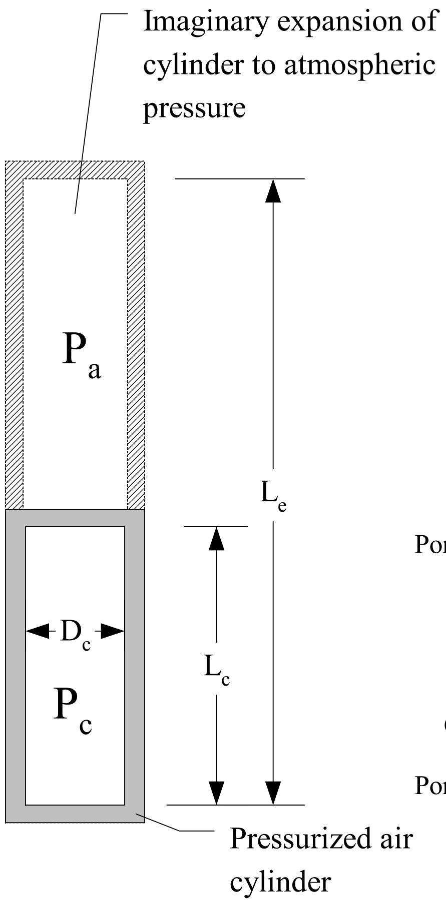
- Pneumatic cylinders are used when cleanliness is important
  - Double acting pistons have different push and pull areas!
  - Speed control is possible with needle valves
    - http://pergatory.mit.edu/2.007/handouts/actuator/piston/piston.html
    - *Remember to use clevis' at ends for couplings!*

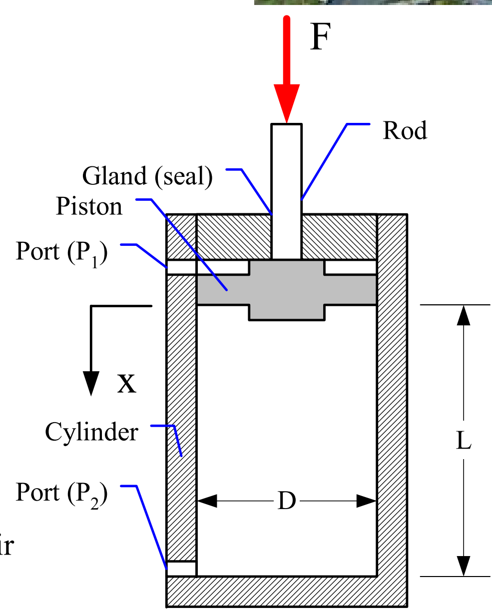


Pneumatic Systems: *Energy Storage*

- How much energy is stored in a pressurized air cylinder?
- How much energy can a pneumatic piston absorb when it is used as a shock absorber or as a spring?
  - ***NEVER use PVC pipe as a piston or energy storage device (see page E-15)***

Pneumatic_pressurized_cylinder.xls			
To determine energy storage in a pressurized cylinder			
By Alex Slocum & Roger Cortesi 1/20/04, last modified 2/16/04 by Alex Slocum			
Enters numbers in **BOLD,** Results in RED			
Cylinder as energy storage device			
Diameter, Dc (mm)	**25**		
Length, Lc (mm)	**101.9**		
Atmospheric pressure, Pa (atm, N/mm^2. psi)	**1**	100000	14.7
Cylinder pressure, Pc (atm, N/mm^2, psi)	**3.0**	300000	44.1
Volume, Vc (mm^3)	**50000**		
Imaginary length to expand to obtain 1 atm pressure, Le (mm)	306		
Energy stored, Ec (Joules=Nm)	6		
Compare to a constant force spring:			
Force, Fspring (N)	**10**		
Spring length, Lspring (m)	**0.40**		
Energy stored, Espring (Joules=Nm)	**4**		
Equivelent number of constant F springs	2		
Height to which a 100 kg professor can be raised (m)	0.00661		



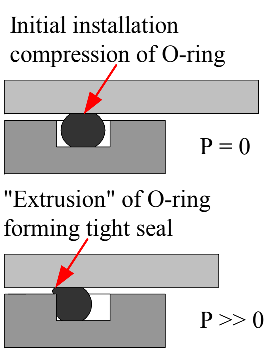


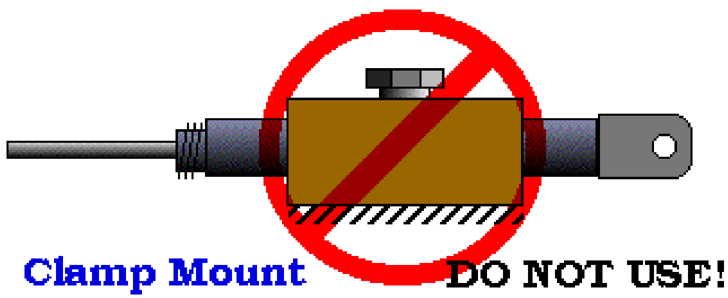
Pneumatic_cylinder.xls			
To determine forces and energy in a pneumatic cylinder (piston)			
By Alex Slocum & Roger Cortesi, last modified 1/20/2004 by Alex Slocum			
Enters numbers in **BOLD,** Results in RED			
Cylinder diameter, d (mm)	**20**		
Rod diamter, dr (mm)	**5**		
Piston stroke (maximum), L (mm)	**50**		
Total volume, V (mm^3)	15708		
Differential area, Ad (mm^2)	295		
Pneumatic cylinder as an actuator			
Piston-side presure, P (atm, N/m^2, psi)	**6**	600000	88.2
Rod-side pressure, Pr (atm, N/m^2, psi)	**1**	100000	14.7
Net pressure force on piston, Fp (N)	143		
Pneumatic cylinder as a compression spring: ISOTHERMAL (constant temperature)			
Initial cylinder pressure, P_1 (atm, N/m^2, psi)	**1**	100000	14.7
Displacement (amount piston compresses gas), x (mm)	**20**	**15**	**10**
Pressure (atm)	1.7	1.4	1.3
Force (N)	21	13	8
Energy absorbed (Joules=Nm)	0.174	0.089	0.036
Pneumatic cylinder as a compression spring: ADIABATIC (NO HEAT TRANSFER)			
Gas (air) properties			
Temperature of the gas at start, T_1a (^{o}C)	**20**		
R, Rgas (J/(kg-K))	**2078**		
cv (J/(kg-K))	**3153**		
γ, gamma	1.65905		
Initial cylinder pressure, P_1a (atm, N/m^2, psi)	**1**	100000	14.7
Displacement (amount piston compresses gas), xa (mm)	**20**	**15**	**10**
Pressure (atm)	2.3	1.8	1.4
Force (N)	42	25	14
Energy absorbed (Joules=Nm)	0.326	0.160	0.063
Temperature of the compressed gas (^{o}C)	28.0	25.3	23.2

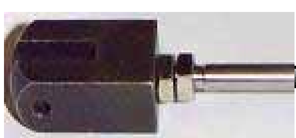
Pneumatic Systems: *Manufacturing*

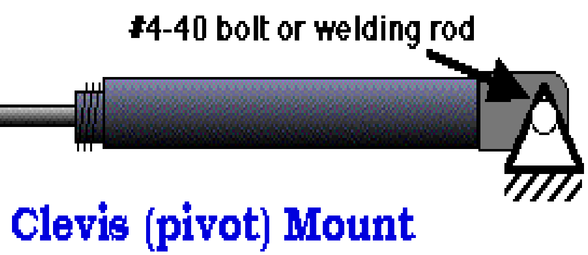
- It is extremely important to avoid over constraint when mounting a cylinder and connecting the rod to the load
  - Clevises provide a means to prevent over constraint
  - DO NOT squeeze the cylinder body or use a set screw!
  - This can change the bore and prevent motion of the piston!
- Seals are a source of friction, lubricate to reduce friction: some lubricants attack seals, and lubes attract dirt, so use a dry lubricant (e.g., Elmer's Slide All™ a Teflon powder lubricant)

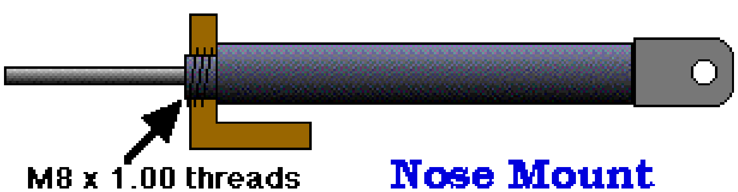
(OK, this picture shows hydraulic pistons, but what ideas does it help you dig up?)



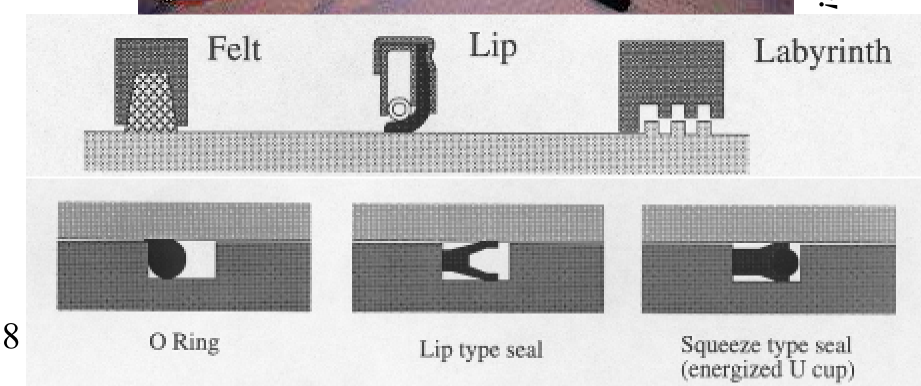






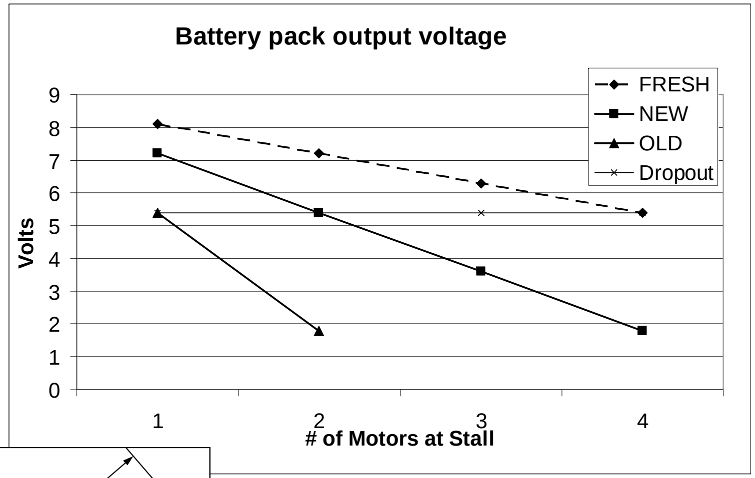


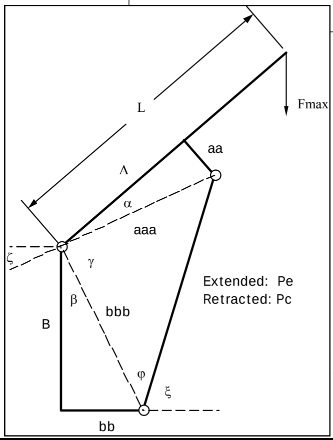
Will Delhagen & Alex Jacobs in MIT's 2001 2.007 contest ***Tiltilator!***

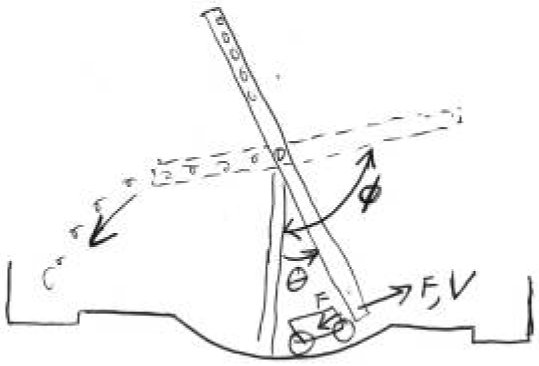


Power Budgets

- Each machine move requires power (force x velocity) and energy (force x distance)
  - Do you have the power?
  - Do you have enough energy?
  - Which motions can you accomplish simultaneously!
- How can you tell if you have enough resources?
  - Create a *Power Budget*
- Beware of internal battery resistance
  - NiCad vs Alkaline…
  - Play with *Power_budget_estimate.xls*



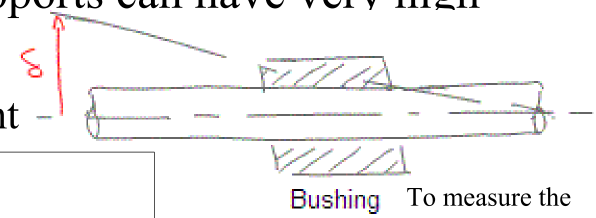




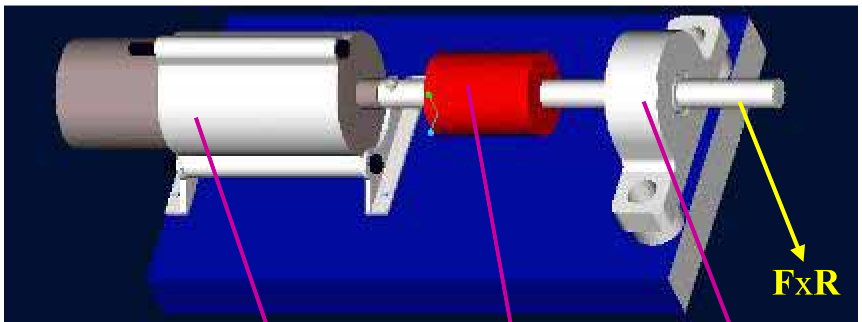
Power_budget_estimate.xls										
Power & energy budget for individual moves, total (S) for simultaneous moves, and cumulative										
Last modified 9/01/03 by Alex Slocum										
Enters numbers in **BOLD,** Results in **RED**						Power (Watts)			Energy (N-m)	
Axis	Move #	Force (N)	Velocity (m/s)	Distance (m)	Efficiency, net system	Move	Battery dissipation	Σ power for move #	Energy for move	Σ Energy
Drive to pucks	**1**	**3**	**0.2**	**1**	**29%**	**2.10**	**8.30**		**52.0**	**52.0**
Lower arm	**1**	**0.5**	**0.5**	**0.04**	**29%**	**0.88**	**8.30**	**11.28**	**0.7**	**52.8**
Scoop	**2**	**3**	**0.2**	**0.02**	**29%**	**2.10**	**3.00**	**5.10**	**0.5**	**53.3**
Raise arm	**3**	**3**	**0.2**	**0.05**	**29%**	**2.10**	**3.00**	**5.10**	**1.3**	**54.5**
Drive to goal	**4**	**2**	**0.2**	**0.5**	**29%**	**1.40**	**3.00**	**4.40**	**11.0**	**65.6**
Dump pucks	**5**	**0.1**	**0.5**	**0.05**	**29%**	**0.18**	**3.00**	**3.18**	**0.3**	**65.9**

Case Study: *System to Measure Gearmotor Performance*

- Gearmotor suppliers do not always provide you with the data you need
- A test system that uses proper couplings and ball-bearing supports can have very high efficiency and thus yield good data
  - Motor efficiency = (mechanical power)/(motor voltage x current



To measure the static friction of a sliding contact bushing, tilt the bushing holding a shaft until the shaft starts to slide, and μ = the tangent of the angle



Design One Gearmotor → Flexible Coupling → Ball bearings

Design Two Gearmotor → Flexible Coupling → Teflon bushing