FUN*da*MENTALS of Design

Topic 5

Power Transmission Elements I

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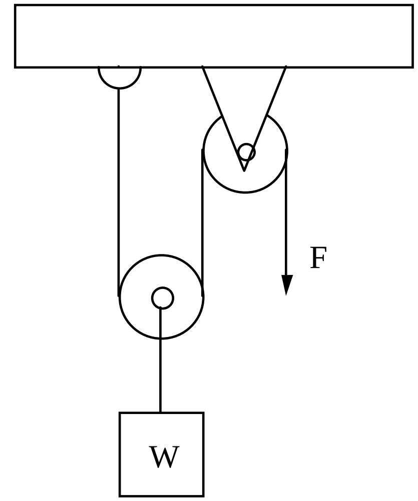
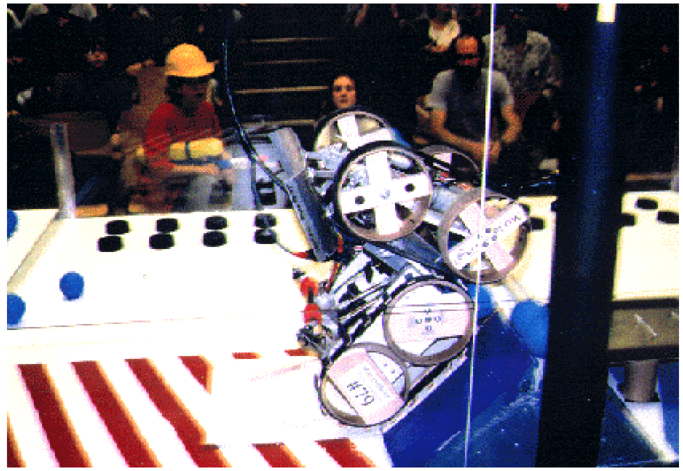
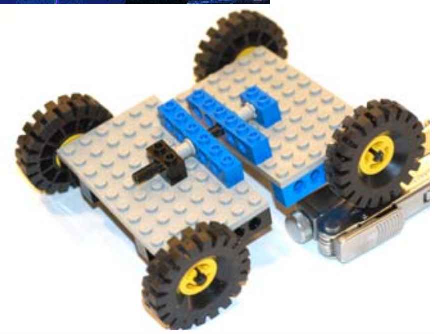
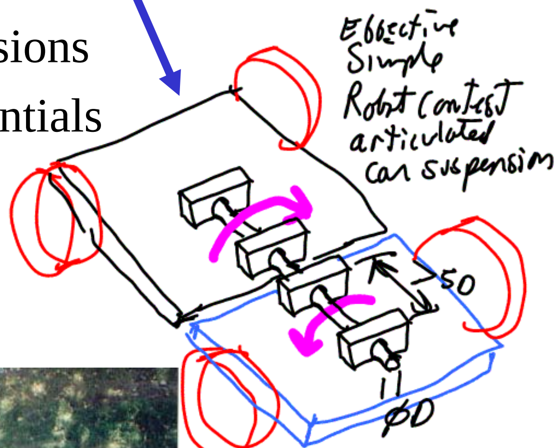
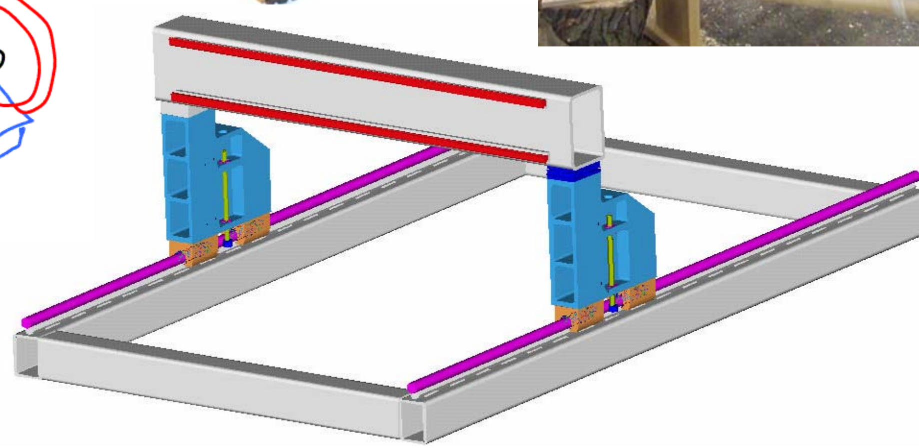


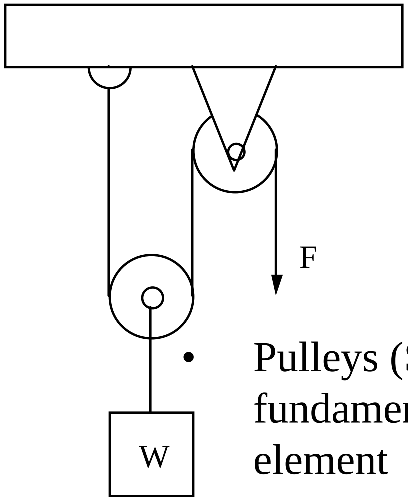


Topics:
- Transmissions
- Pulleys
- Winches
- Belts & Cables
- Wheels
- Steering & Suspensions
- Clutches & Differentials
- Cams
- Shafts
- Couplings

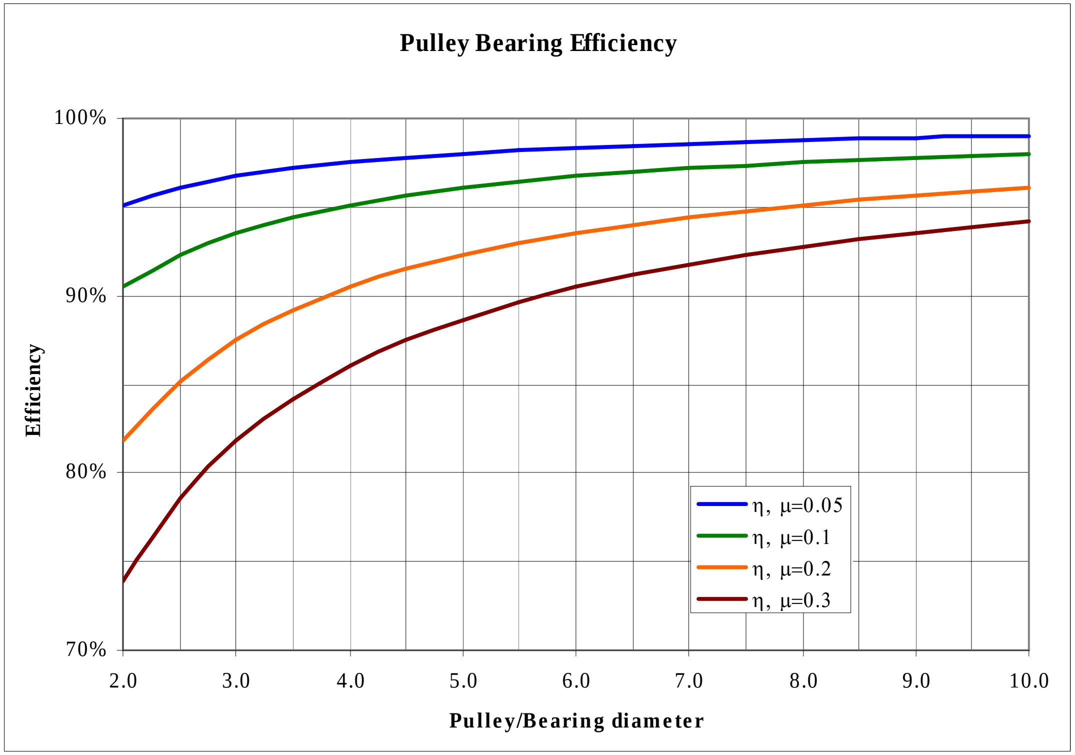




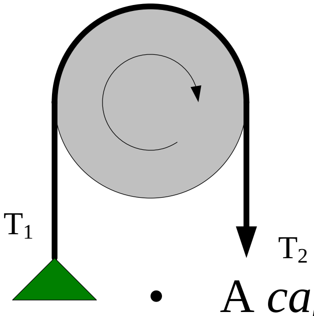




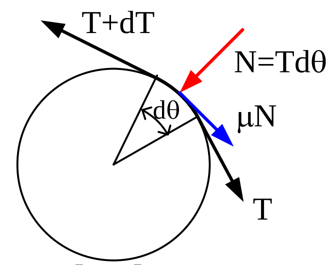
Pulleys



- Pulleys (Sheaves) are a most fundamental power transmission element
  - Mechanical advantage
  - Capstans
  - Efficiency
  - Tracking
  - Mounting



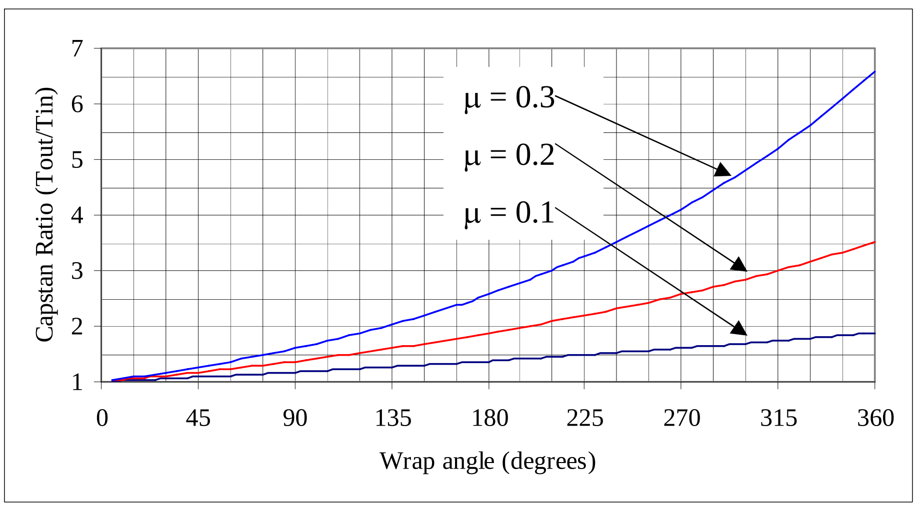
Pulleys: *Capstans*



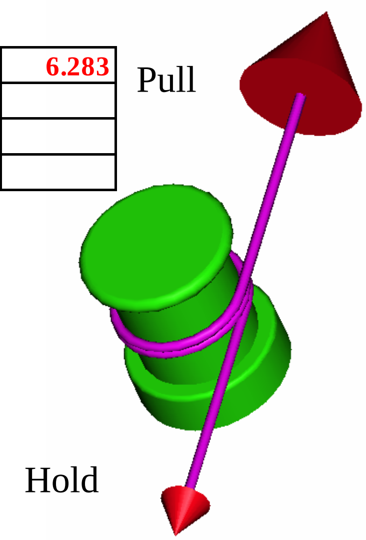
- A *capstan* is typically a fixed, or controlled rotation, body-of-revolution which a cable wraps around
  - A capstan can also form the basis for a band brake, where a band is anchored to a structure, and then wraps around a shaft…
- A cable wrapped around a capstan by θ radians with coefficient of friction m and being held with a force F_{hold}, can resist the pull of a cable with many times higher force F_{pull}

$$F_{hold} = F_{pull} e^{-\mu\theta}$$

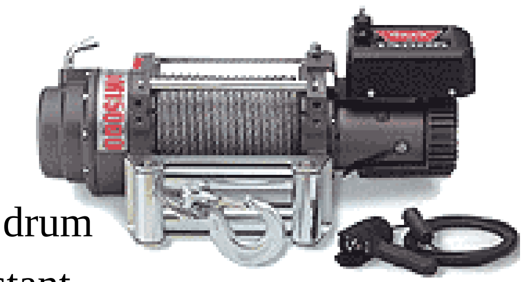
- If a belt or cable runs around a fixed shaft, then there is a lot of friction between the belt and the shaft, and the efficiency is low:



Angle of wrap (degrees, radians) θ	**720**	**6.283**
Coefficient of friction μ	**0.2**	
Holding force Fhold	**1**	
Pulling force that can be resisted Fpull	**3.52**	

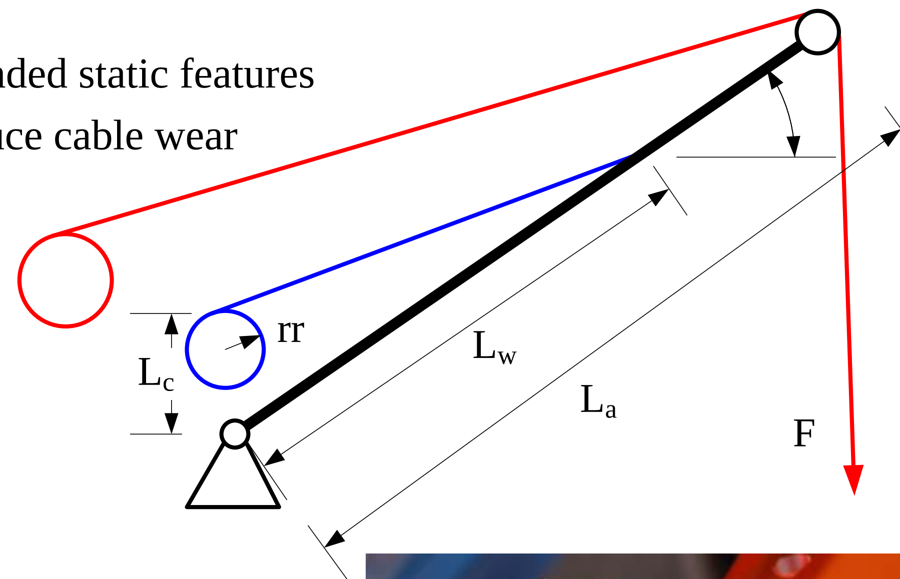


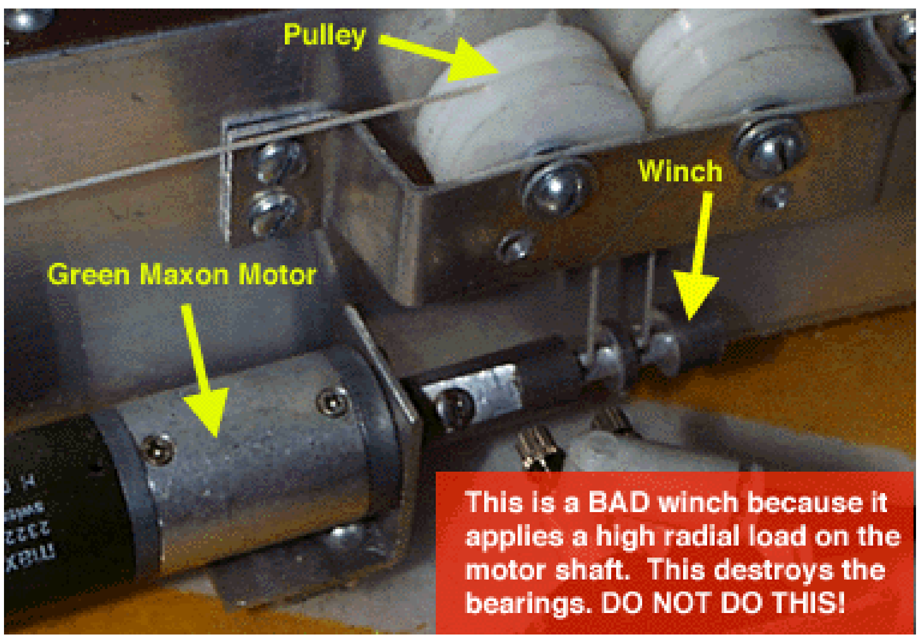
Winches

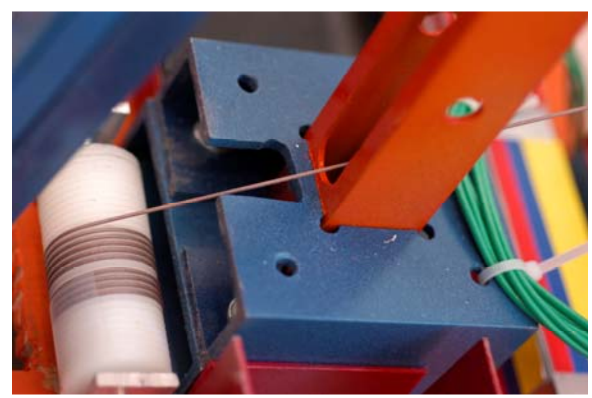


http://www.gowarn.com/winches.htm

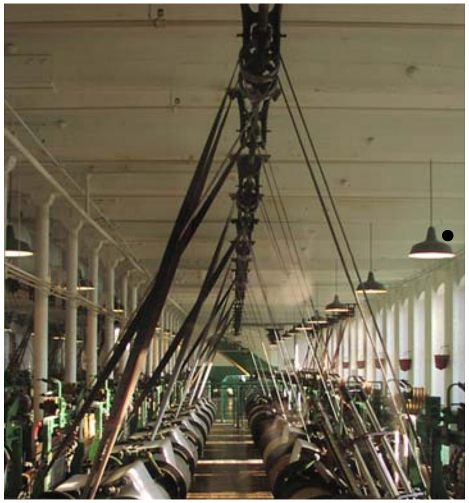
- A winch is a motorized drum that controls cable tension
  - A single wrap of cable on the drum requires a long or large diameter drum
    - Effective drum diameter and winch force capability remain constant
  - Multiple wraps of cable on the drum allow for more cable in a smaller place
    - Drum diameter and winch force capability vary
  - A fairleader is a device to control the input/output of the cable so it winds on the drum in an orderly fashion
    - The simplest design just uses smooth rounded static features
    - Vertical and horizontal roller designs reduce cable wear







Belts & Cables



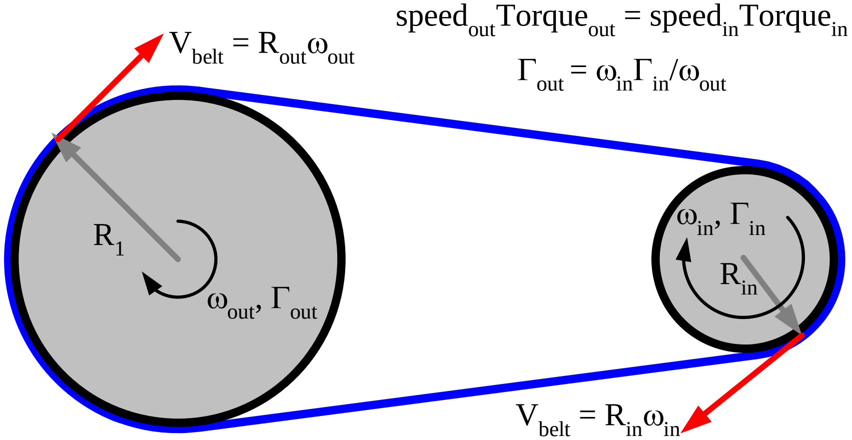
Thanks to Prof. John Lienhard for this photo!

- Applications and Engineering
  - Linear motion
  - Rotary motion
  - Crawler tracks
  - Manufacturing & Assembly

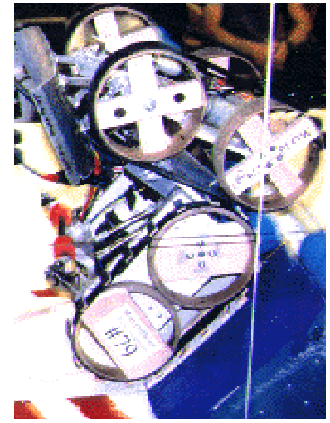
$$\text{Power}_{out} = \text{Power}_{in}$$

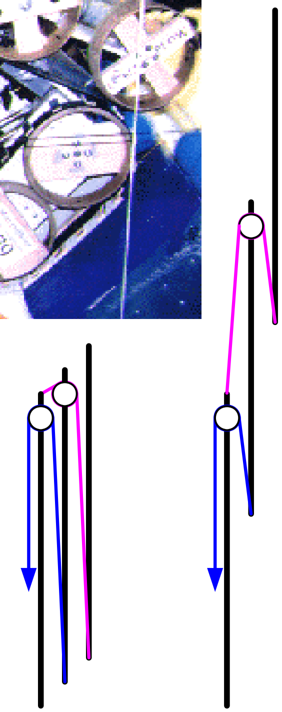
$$\text{speed}_{out}\text{Torque}_{out} = \text{speed}_{in}\text{Torque}_{in}$$

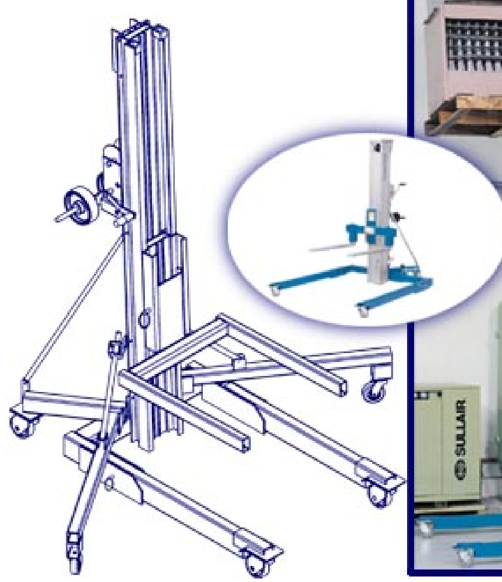
$$\Gamma_{out} = \omega_{in}\Gamma_{in}/\omega_{out}$$



Bishop Brady High School FIRST robotics team 2005 robot (Prof. Slocum was the coach)





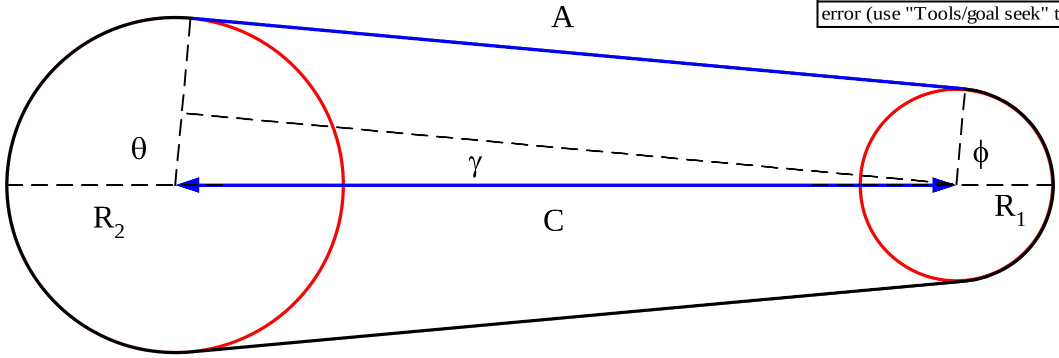


http://www.genielift.com/ml-series/ml-1-5.html

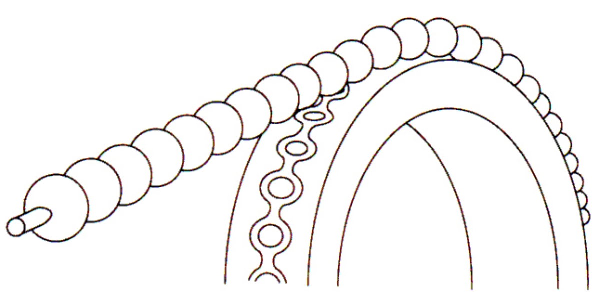
Belts & Cables: *Stress, Tension, & Center Distance*

- Belts and cables are very robust elements, but they require engineering of 3 basic details:
  - Stress from wrapping a belt or cable around a pulley
  - Tension in the belt or cable
  - Center distance between pulleys

pulley_center_distance.xls			
By Alex Slocum, last modified 2/19/04 by Alex Slocum			
Pulley Center Distance Calculation			
Enters numbers in **BOLD**, Results in RED			
	Toothed belt		
Belt pitch, P	**0.2**		
Number of teeth on belt N	**100**	Enter the number of teeth on the belt, if center distance ends up being too small, increase number of teeth	
Start with a guess for C, and then use Goal Seek			
Desired center distance, C	8.24		
Large pulley pitch radius, R2	**0.5595**		
Small pulley pitch radius, R1	**0.5595**		
Length of belt, Lt, Lf	20		
Tangent segment, A	8.2423		
gamma, g	0.0000		
Phi, f	1.5708		
Theta, t	1.5708		
error (use "Tools/goal seek" to set value of B17 to zero by changing B9)	0.000		



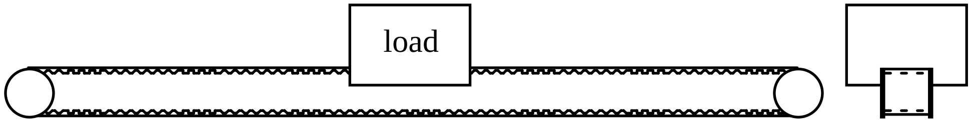
Bandstress.xls	
By Alex Slocum	
Last modified 4/22/02by Alex Slocum	
Stress in a flat belt wrapped around a pulley	
Enters numbers in BOLD, Results in RED	
Belt parameters	
Thickness, t (mm)	**0.10**
Width, w (mm)	**5**
Modulus, E (N/mm^2)	**2.00E+05**
Poisson ratio, n	**0.29**
Forces	
Load to be carried, F (N)	**10**
Belt stress, sigF (N/mm^2)	20.0
Pulley wrap stresses	
Pulley diameter, D (mm)	**50**
stress	437
Motor torque required (N-mm)	250
Capstan effect	
coefficient of friction, mu	**0.2**
Wrap angle, q (degrees)	**180**
required pre-tenion, pT (N)	5.3
Belt stress, sigT (N/mm^2)	10.6
Total stress	467
Total strain	0.23%
Check: Tension in the belt (pluck it like a guitar string)	
Measured frequency of lateral vibration (hz)	**150**
Free-length (mm)	**300**
density (g/mm^3)	**7**
mass per unit length (g/mm)	0.004
Tension (N)	7.1



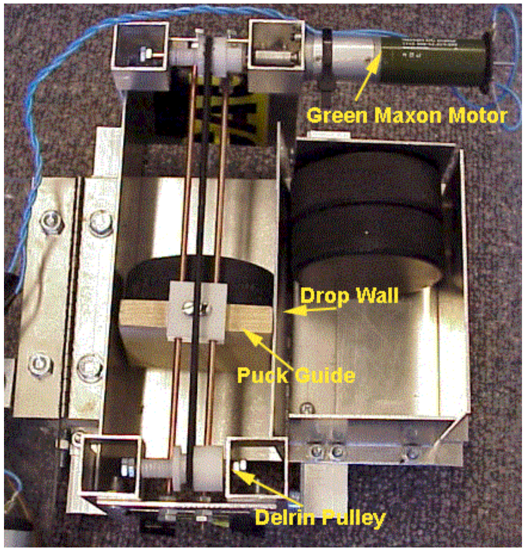
Bead belt drive

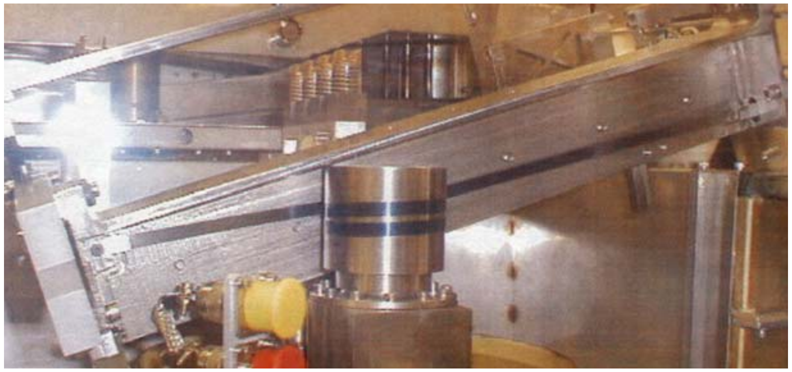
Belts & Cables: *Linear Motion*

- Belts & Cables are a effective way to convert rotary to linear motion

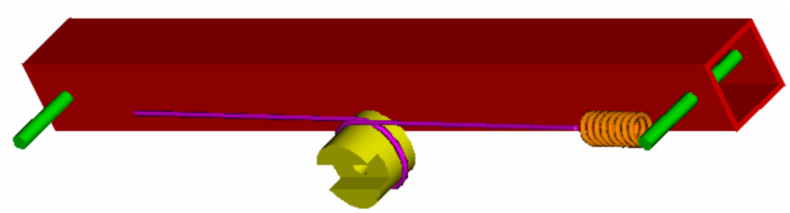


- The force F in a belt with tension T on a pulley of diameter D that can be generated by the torque Γ can be conservatively estimated by:
  - $F = 2\Gamma/D$ *for toothed belts,* and $F = T\mu D/2$ *for flat belts*
    - A more exact model would consider the capstan effect
    - Play with *bandstress.xls*
  - The speed is simply
    - $V_{linear}=\omega_{motor}*D/2$
- Belts run on pulleys
  - For flat belts, pulleys must be crowned to accommodate misalignment
  - Timing belt pulleys must be aligned to prevent premature failure

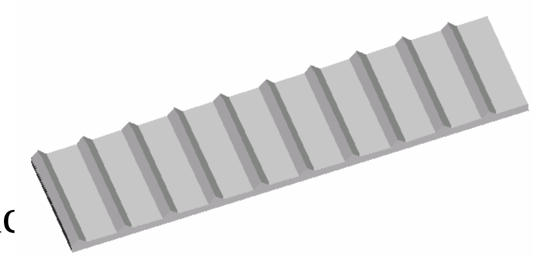




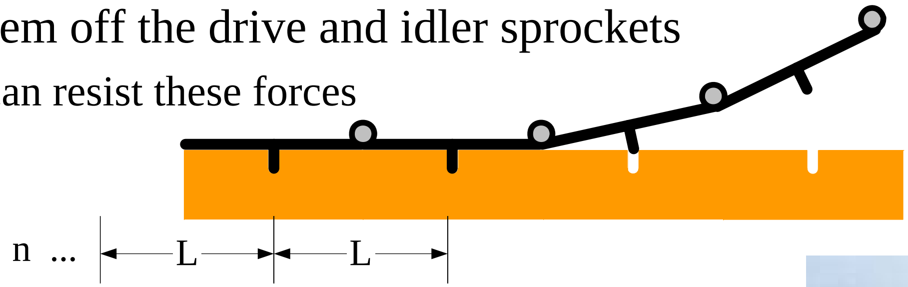
Should this metal belt driven axis be at this angle? NO, it was the software (honest) that made the vertical axis plange while the metal belt driven horizontal axis was still extended…

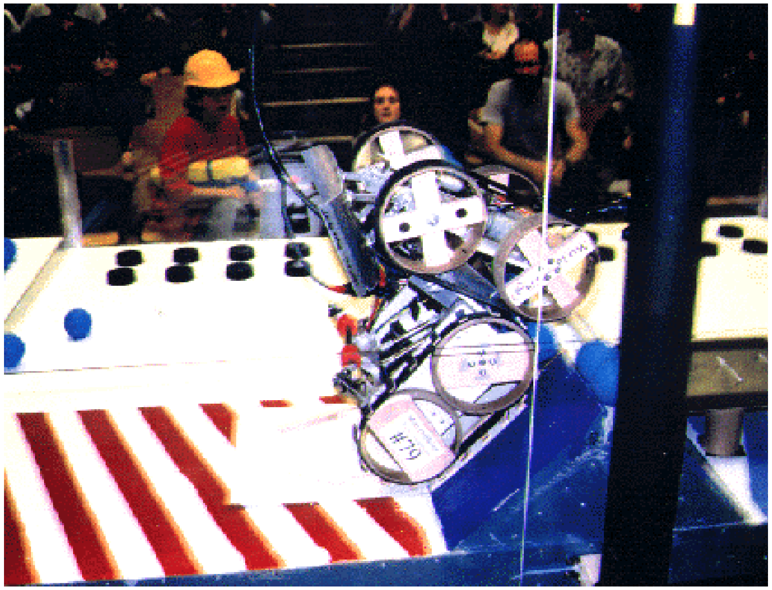


Belts: *Crawler Tracks*

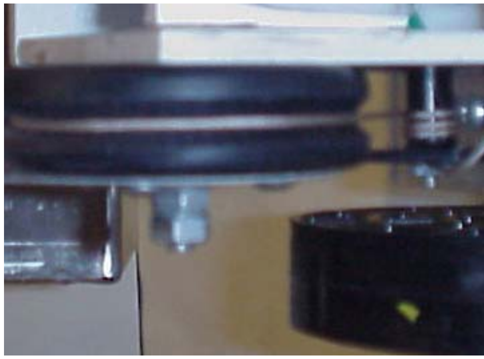


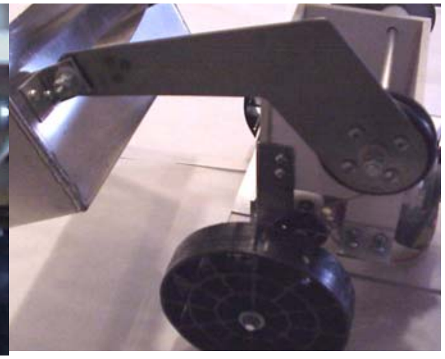
- Tracks only help when there is loose media or a surface into whic
- Tracks (and treads) DO NOT help on smooth surfaces
  - Smooth surfaces often are covered with a dust layer, and sharp-groove treads can help
  - Treads can be created by cutting angled slices from a rubber strip, and gluing them onto the belt surface
- Tracked vehicles skid steer, and as a result there are large normal forces on the tracks which try to pull them off the drive and idler sprockets
  - A central ridge can resist these forces



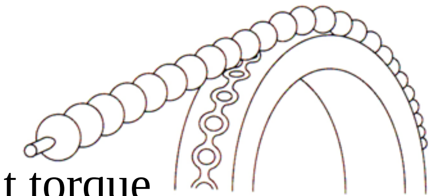


www.caterpillar.com





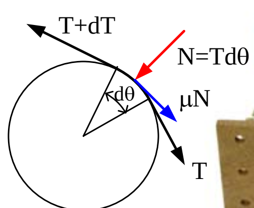
Belts & Cables: *Rotary Motion*

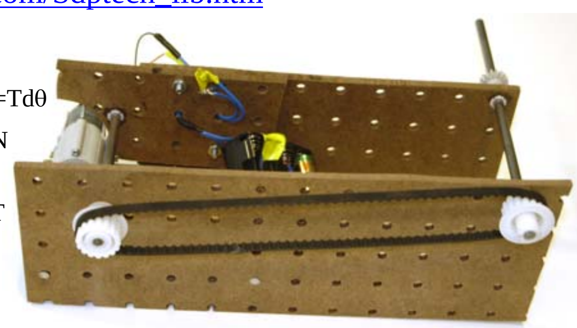


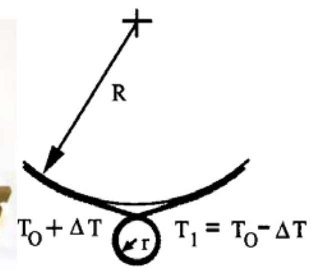
Bead belt drive

- Flat belts and cables (string drives) require higher tension to transmit torque
  - Conservatively, the belt needs to be held in tension equal to the desired torque divided by the coefficient of friction and the small pinion radius
- Vee-belts use the the *principle of self help*:
  - Increased tension caused by power being transmitted, wedges the belt in a Vee-shaped pulley groove, so it can transmit more torque…
- *Synchronous Drives (timing, gear, ladder belts)* can transmit torque between shafts and also achieve a transmission ratio
  - They combine the positive timing action of gears with the flexibility, speed and low noise level of belts
    - For an in-depth discussion on synchronous drive design, see Stock Drive Products on-lir http://www.sdp-si.com/Sdptech_lib.htm

Ken Stone, Director of the MIT Hobby Shop, and his string-powered lathe web.mit.edu/hobbyshop





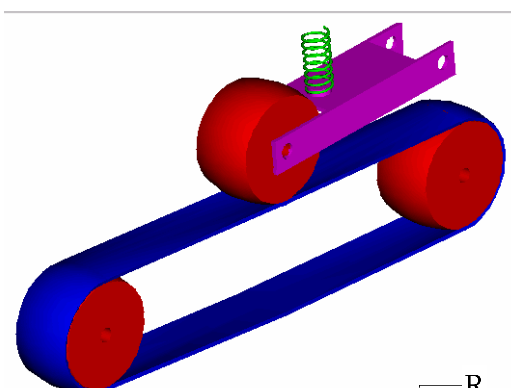


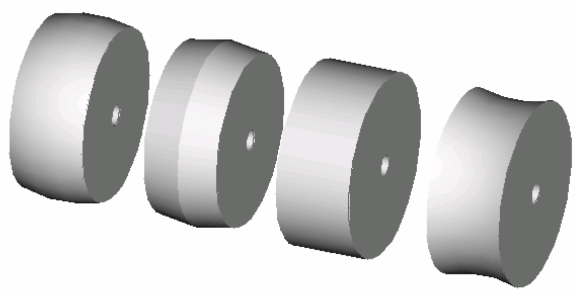
Roto-Lok drive from Sagebrush Technology Inc.

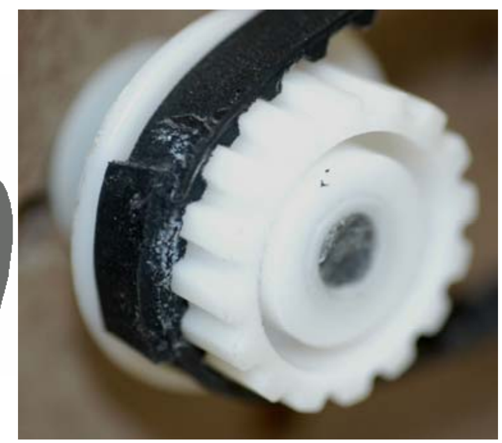
–http://www.sdp-si.com/Sdptech_lib.htm

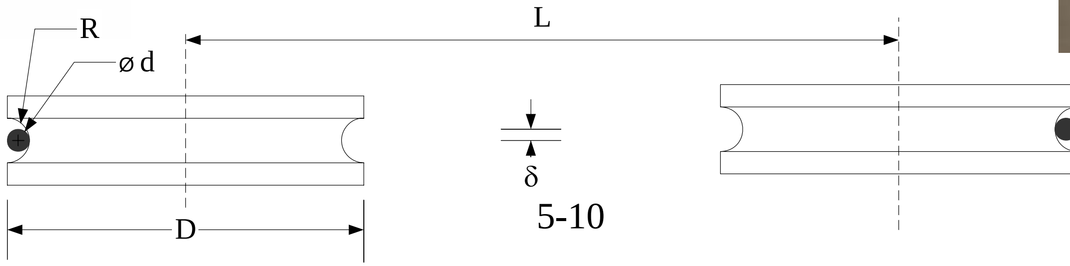
Belts & Cables: *Manufacturing & Assembly*

- Misaligned pulleys increase wear and decrease life!
- Two pulleys' axes of rotation can never be perfectly parallel, so a flat belt will want to drift off (tracking)
  - Pulleys must be crowned (round profile) to keep a belt from walking off
    - On a concave surface, the side with more belt in contact will cause the belt to drift further to that side until it falls off
    - A flat pulley is at best neutrally stable
    - Great, OK, bad, & horrid pulleys:
  - Tension must be maintained either by proper pulley center distance and belt elasticity, or a mechanism to tension the pulleys or a pulley that pushes sideways on the belt

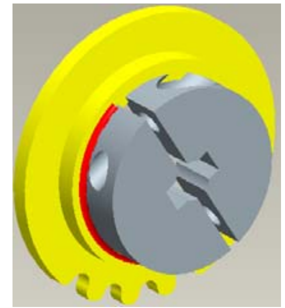




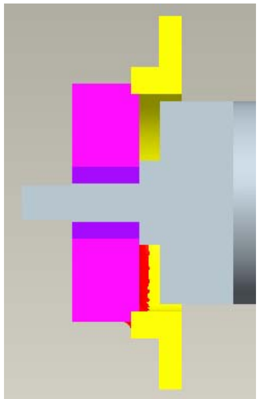


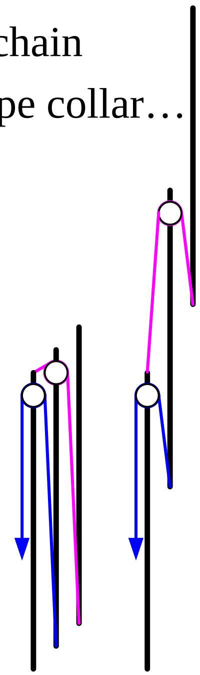


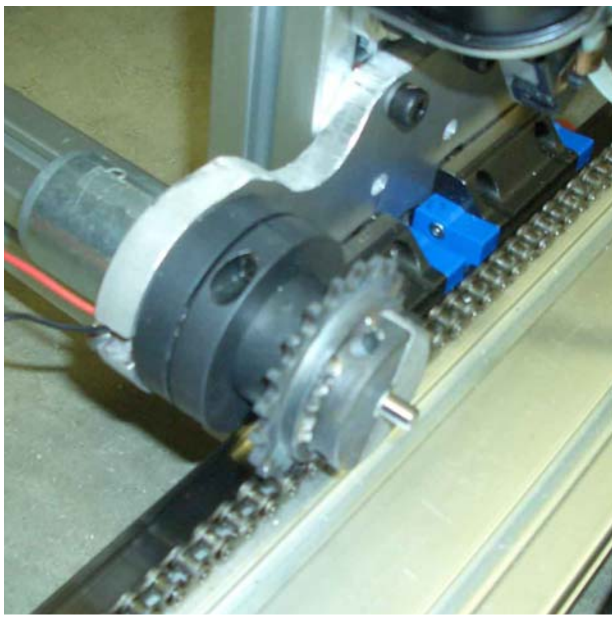
Chains



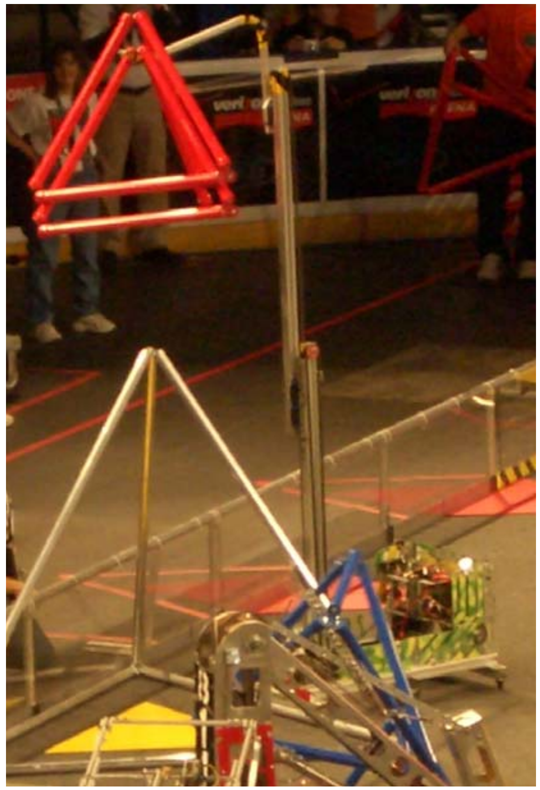
- Chains are a very robust means to transmit very large forces and torques
  – Rotary-to-rotary motion is very common (look at your bicycle!)
  – Rotary-to-linear motion can be obtained by laying a chain on a surface, and anchoring each end with bolts through the links
    - A sprocket mounted to the motor "crawls" along the chain
    - The sprocket can be welded or bolted to a squeeze-type collar…
  – Linear-to-linear motion for extending axes
    - Idler pulleys are invaluable

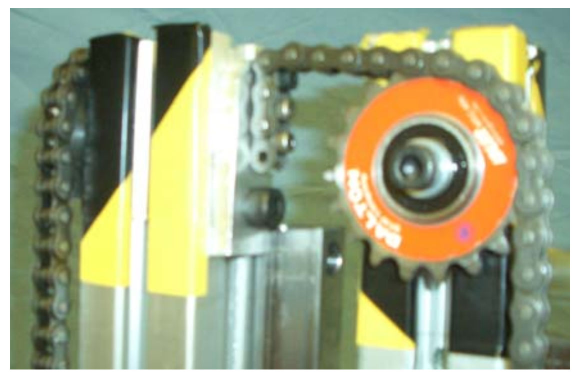






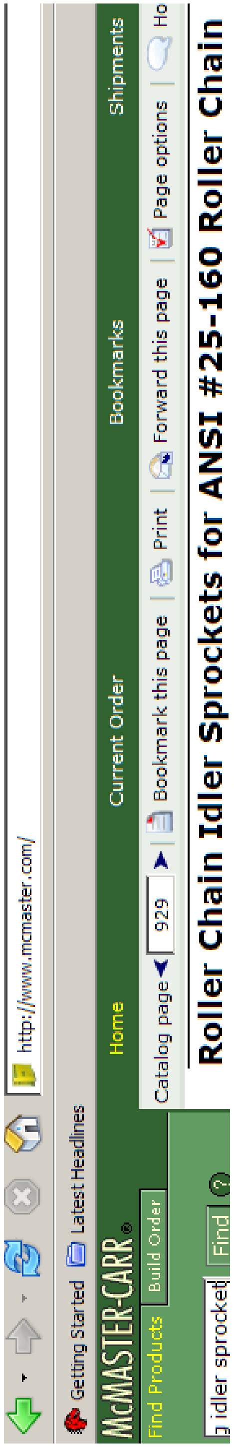
Bishop Brady High School's rookie FIRST robotics team used chain drives to realize a very simple and effective robot that earned the *Rookie All Star* Award and *Top Rookie Seed* awards at the 2005 Manchester regional competition and a trip to the finals in Atlanta.

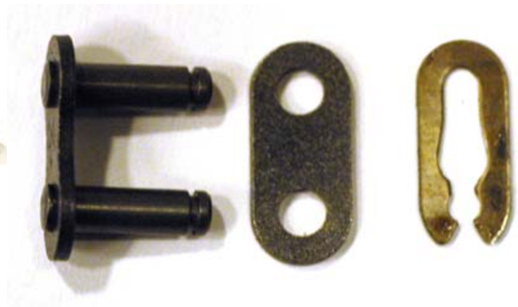




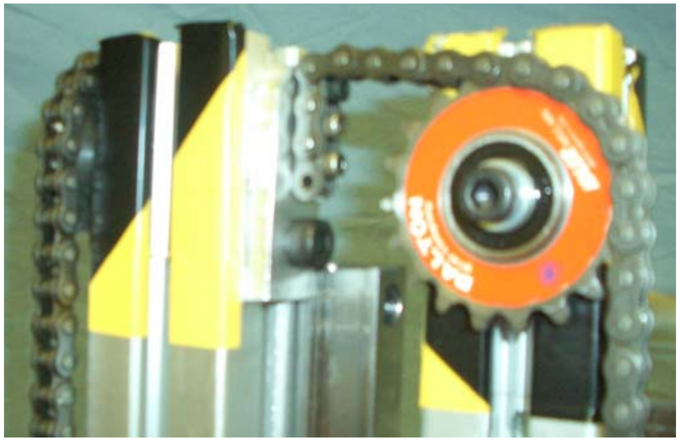
Chains: *Engineering*

- There are many different components that designers can use to create systems
- A *chain breaker* (a press) pushes out the roller chain's pin
  - Master links are used to splice chain ends together to form desired length loops
    - Master links are available with fittings to allow things to be attached to the chain

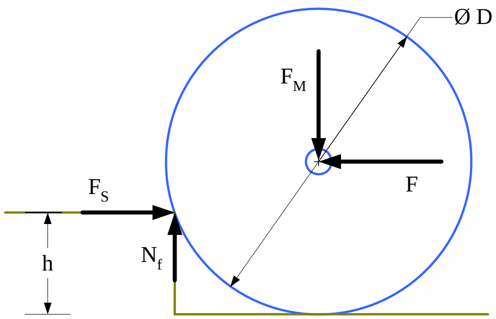


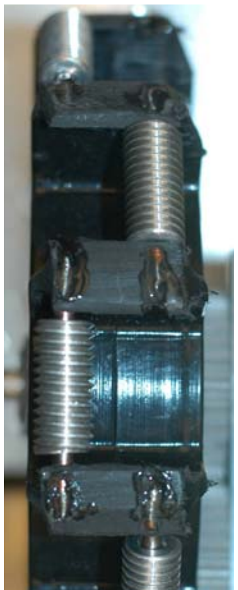


- Idler pulleys allow for routing of the chain
  - Idler pulleys can have integral ball bearings
  - A bolt through the center supports and anchors the idler pulley

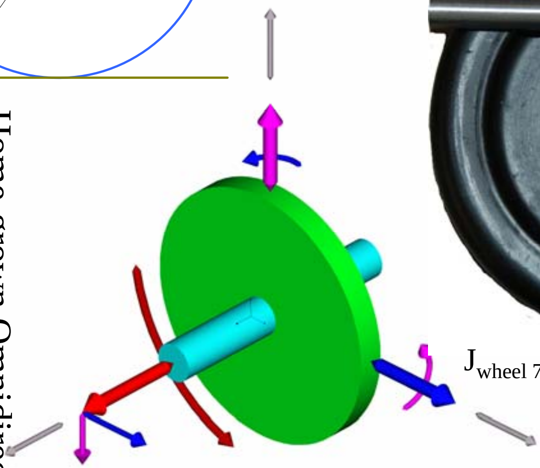


Wheels

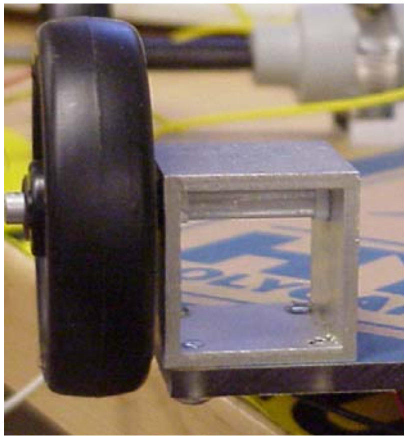




Home-grown Omnidirectional wheel



$J_{\text{wheel 75 mm diameter}}$ = 7.1e-5 kg*m^2



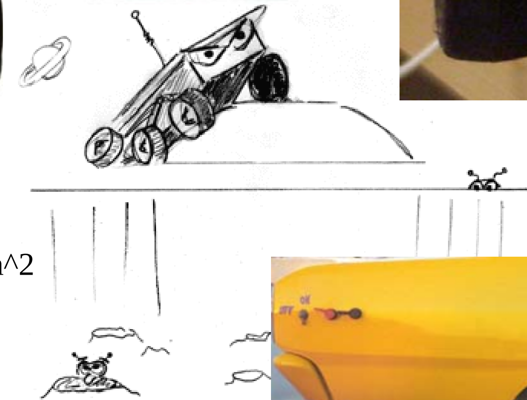
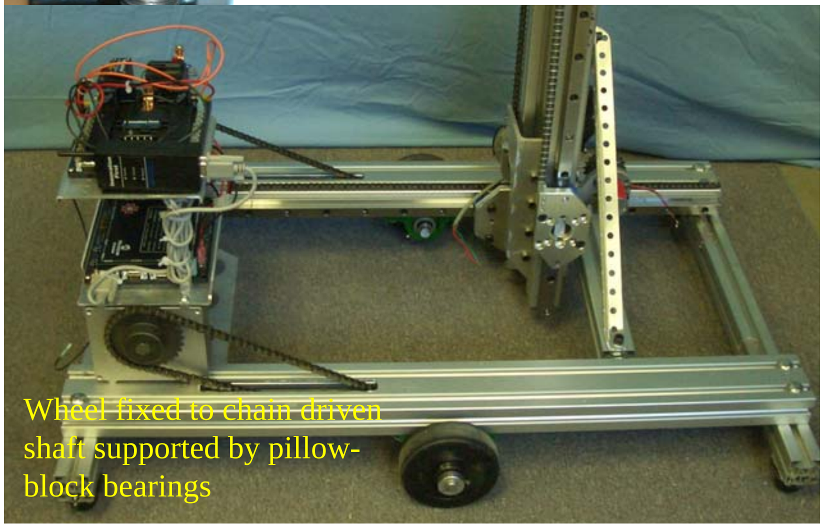
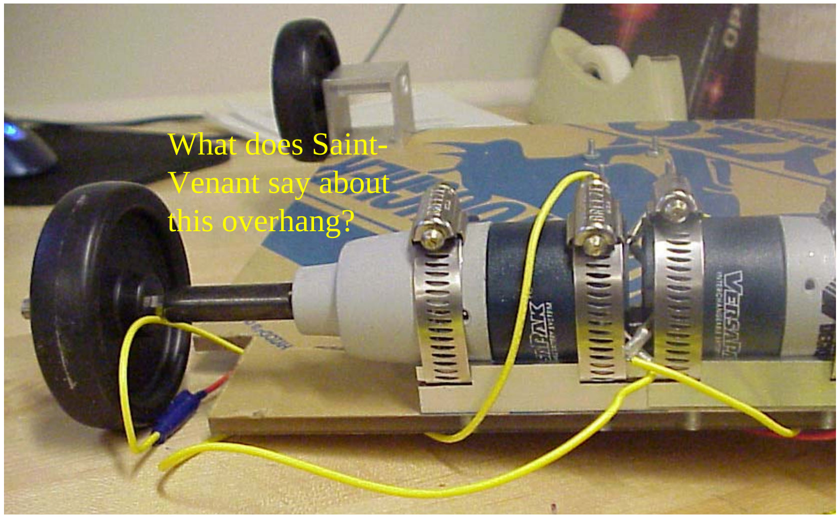


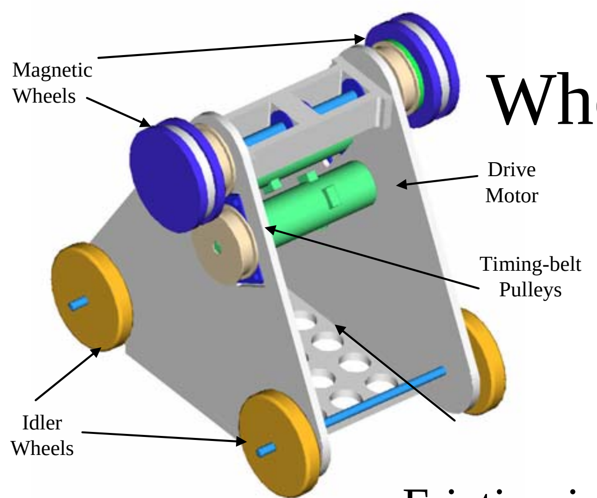
Photo by Rick Slocum www.100jpegs.com

- Traction & Controllability
- Size, Torque & Contact Pressure
- Manufacturing & Mounting

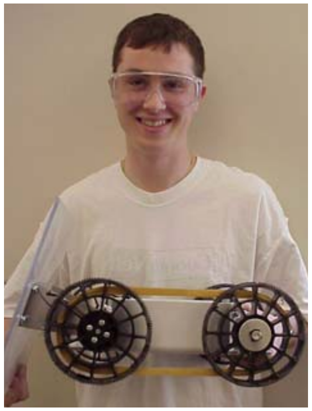


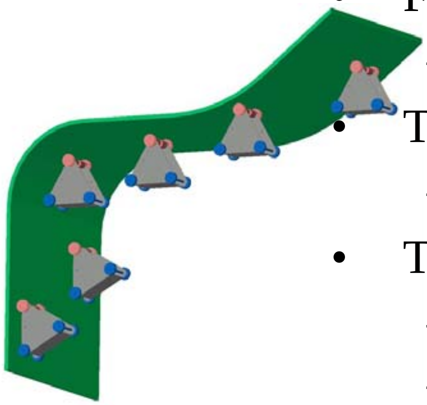


Wheels: *Traction & Controllability*

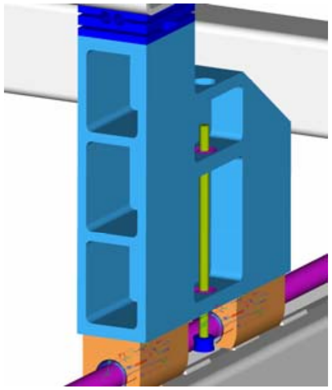


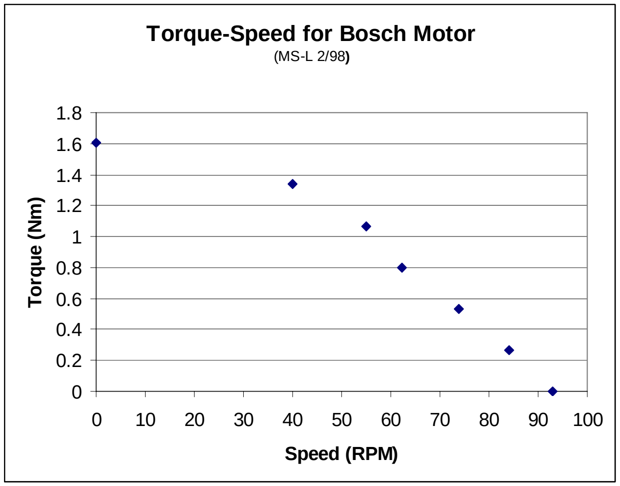
Nick Powley obtained 4WD by cutting grooves in his wheels and using rubber bands as drive belts…





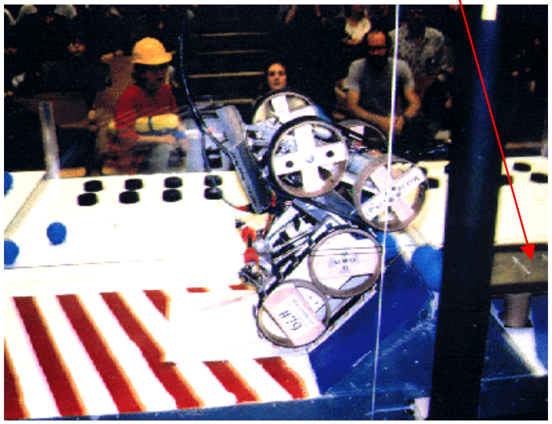
- Friction is independent of surface finish, unless there is physical engagement
  - Like gear teeth on a rack, sandpaper grips carpet, plastic…
- Two-Wheel Drive vehicles are simple to build
  - Against a 4-Wheel Drive or a Tracked vehicle, they lose
- The smaller the wheel:
  - The greater the traction force the motors can cause
  - The slower the vehicle per unit input to the controller!





Tom Slowe made a very successful 2WD vehicle with sandpaper covered rear driven wheels

Tim Zue's sandpaper covered platform enabled him to get to the other side every time!



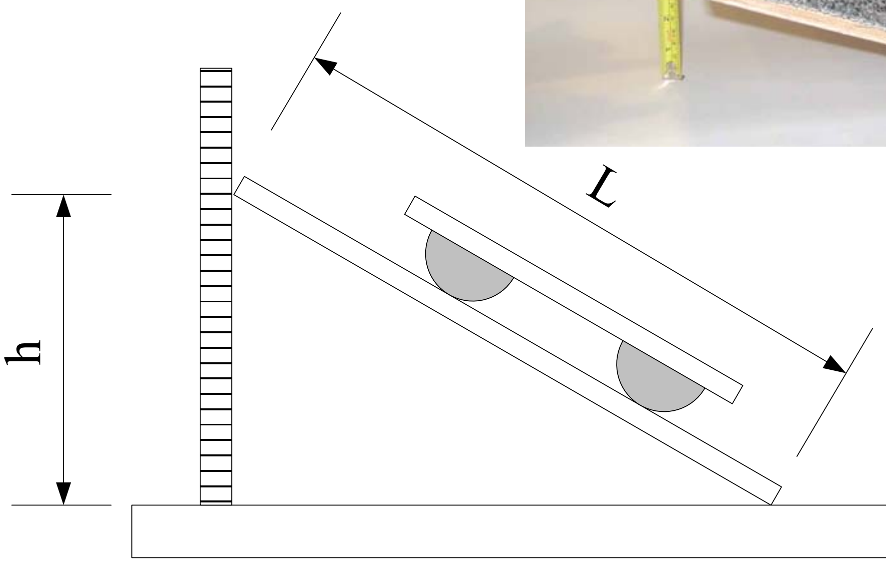
Wheels: *Coefficient of Friction*

- Simple inclined plane tests were done
- Hypotenuse length = 400 mm
- Raise end of ramp till test car slips:

$$\mu = \tan\theta = \frac{h}{\sqrt{L^2 - h^2}}$$

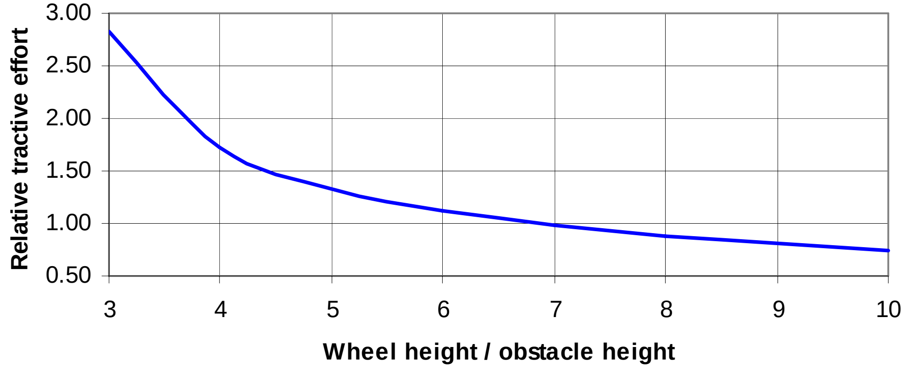
	Surface		
Coefficient of friction	Plywood		Carpet
Wheel surface	along grain	across grain	
Plain	0.45	0.47	0.31
Knurled	0.47	0.48	0.64
Sandpaper covered	0.91	0.92	1.81

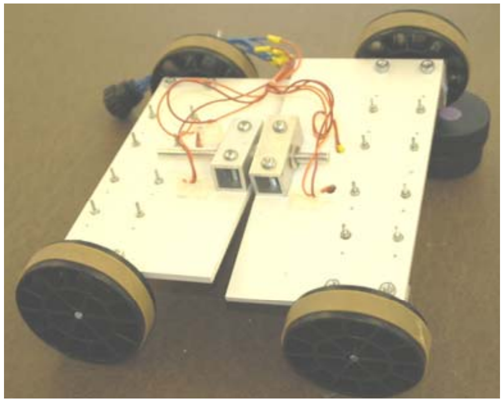
  – The sandpaper covered wheel tester on carpet did not actually slip, it tipped!

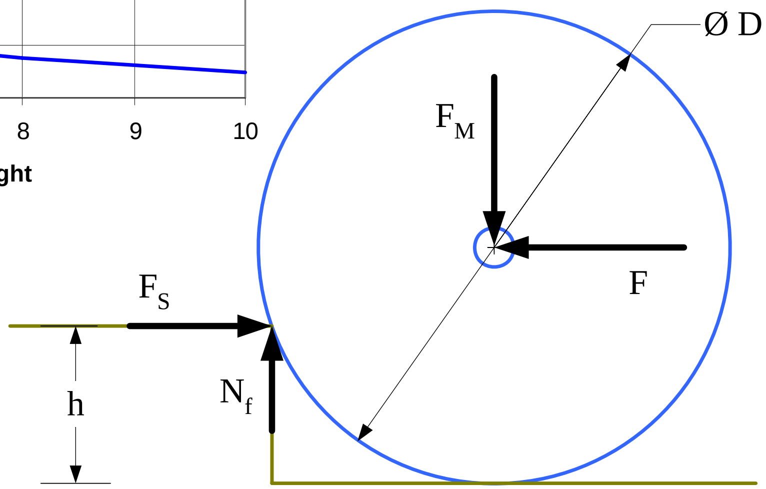


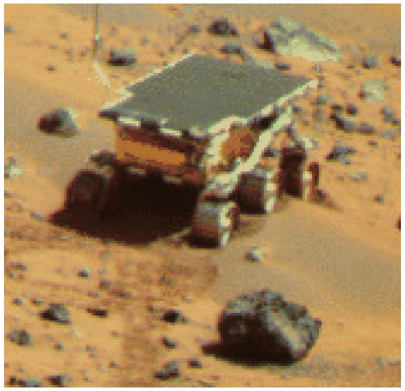
Wheels: *Size, Torque and Contact Pressure*

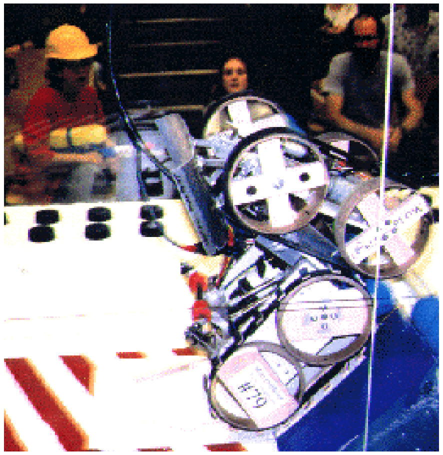
- How big must a wheel be to make sure it can overcome obstacles?
  - The smaller the wheel diameter, the lower the torque to turn it
    - Ideally, the wheel just slips when maximum torque is applied
      - This keeps you from stalling the motor and potentially burning it out
  - The smaller the diameter, the higher the contact pressure, and the greater the wear
    - Hertz Contact stress theory can determine if wheels are too heavily loaded!
    - The bigger the wheel, the easier it is to drive over an obsticle
    - See *Wheelclimb.xls*

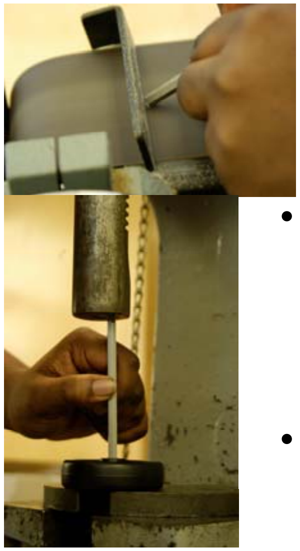






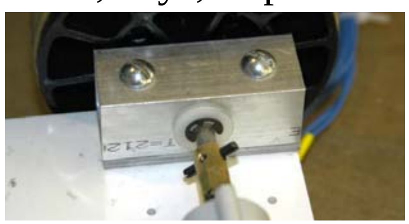


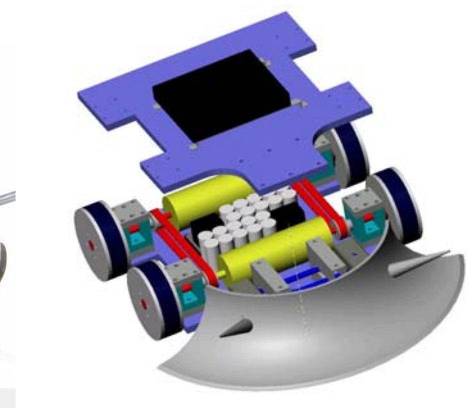




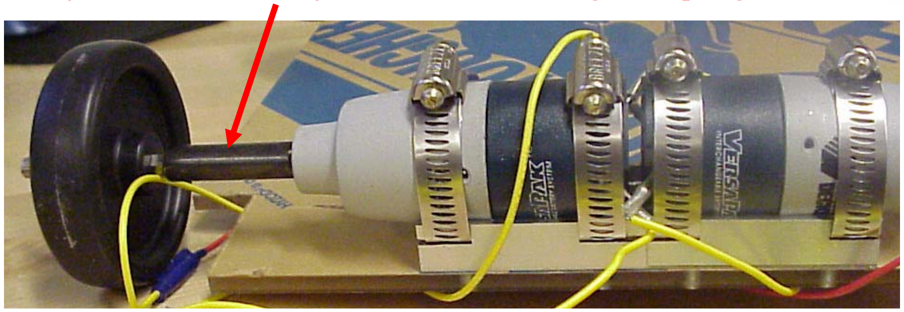
Wheels: *Manufacturing & Mounting*

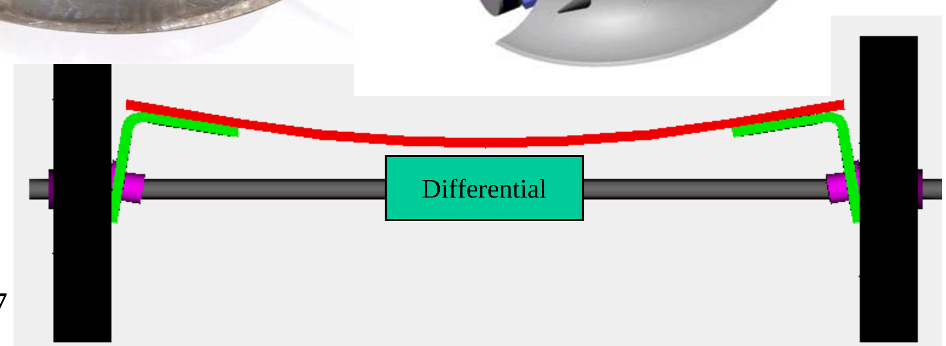
- A positive engagement is required to effectively transmit torque from a shaft to a wheel
  - A hexagon hole can be broached into pulleys and wheels
  - Square and hexagon shafts can be threaded!
  - A round shaft's ends can be machined square to fit into a square-broached hole
- The wheel-on-shaft subassembly should overhang the gearbox as little as possible!
  - If the overhung shaft has a lot of compliance, an "outrigger" bearing can be added without over constraining the shaft, if it confines the shaft to its nominal central position
- Beware of system deformations and the fact that they can take up all the clearance in a system and cause it to bind
- E-clips are a great way to retain thrust washers
- Press-fits, keys, or pins transfer torque



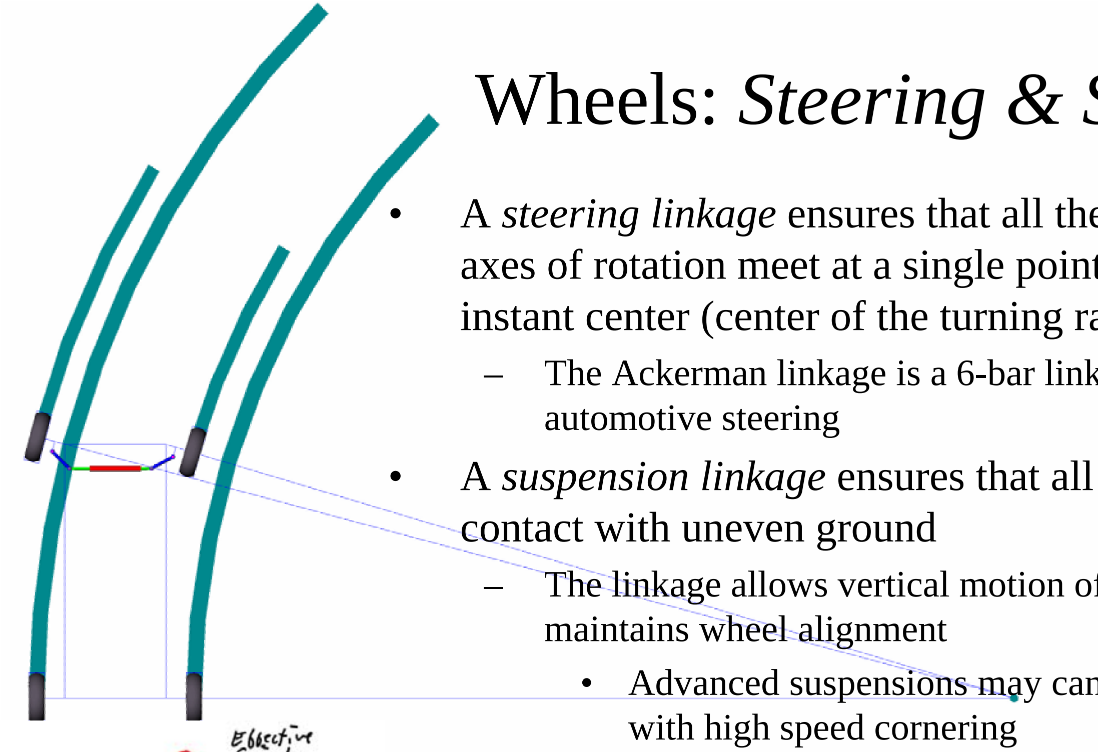


Too much overhang (remember Saint-Venant!). Consider the use of an outrigger bearing, or mount the wheel on a properly supported shaft and drive the shaft with the motor using a coupling





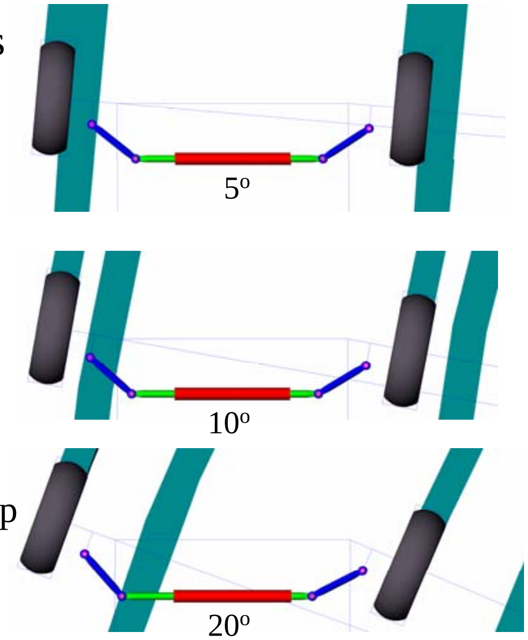
Wheels: *Steering & Suspensions*

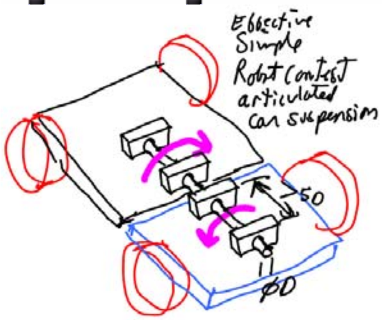


- A *steering linkage* ensures that all the vehicle's wheels axes of rotation meet at a single point, which is the instant center (center of the turning radius)
  - The Ackerman linkage is a 6-bar linkage developed for automotive steering
- A *suspension linkage* ensures that all wheels keep contact with uneven ground
  - The linkage allows vertical motion of the wheel, but maintains wheel alignment
    - Advanced suspensions may cant (tilt) wheels to help with high speed cornering
  - Recall page 3-26 and the concept of elastically averaged design

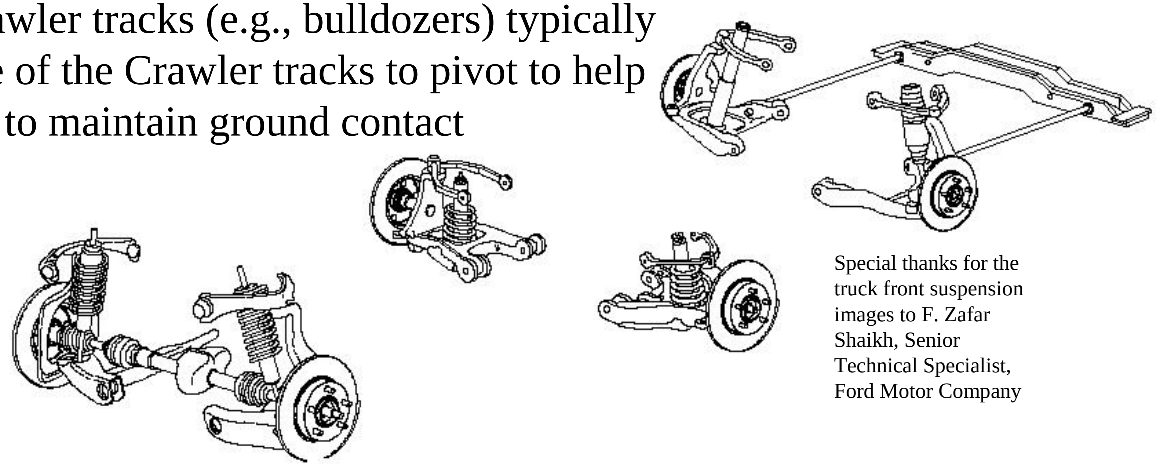
Instant center

- Vehicles with crawler tracks (e.g., bulldozers) typically allow at least one of the Crawler tracks to pivot to help ensure the treads to maintain ground contact

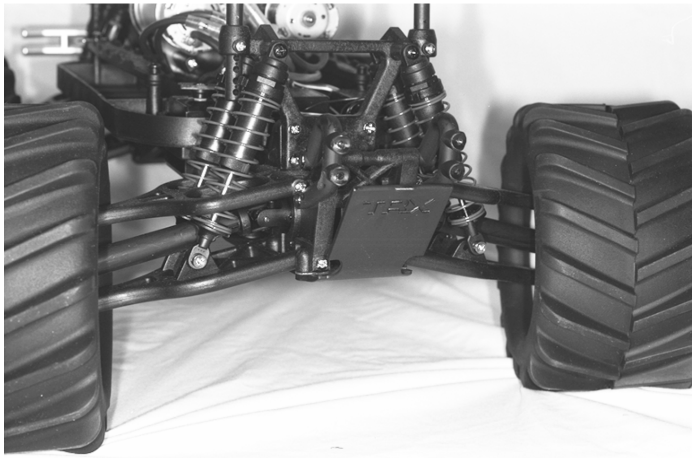


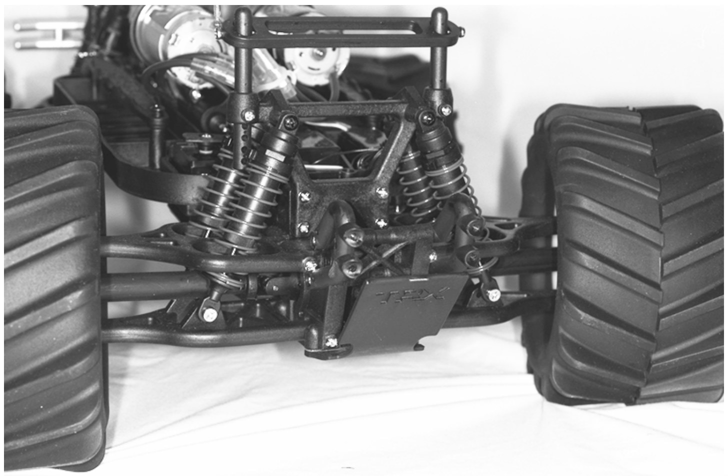


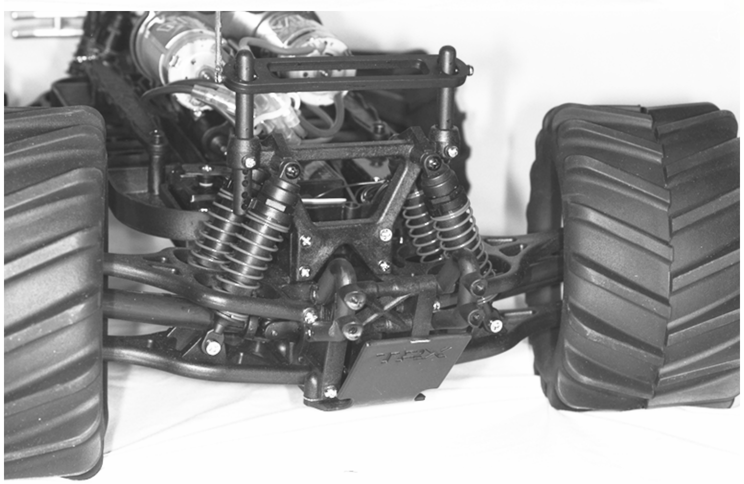
http://www.cannondale.com/bikes/02/cusa/



Special thanks for the truck front suspension images to F. Zafar Shaikh, Senior Technical Specialist, Ford Motor Company

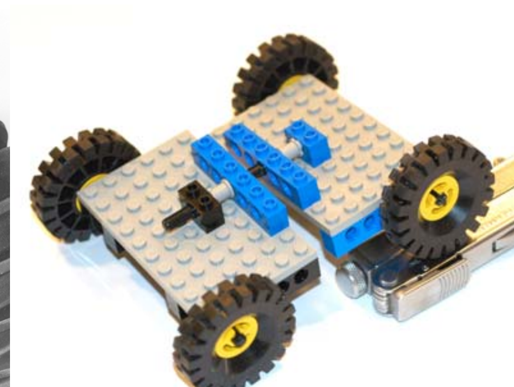


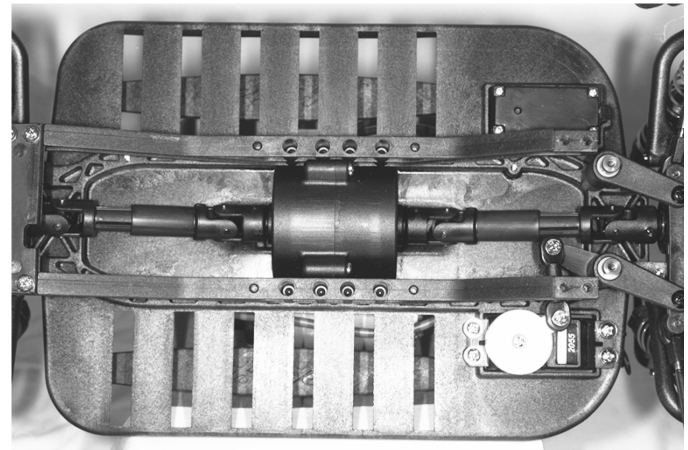


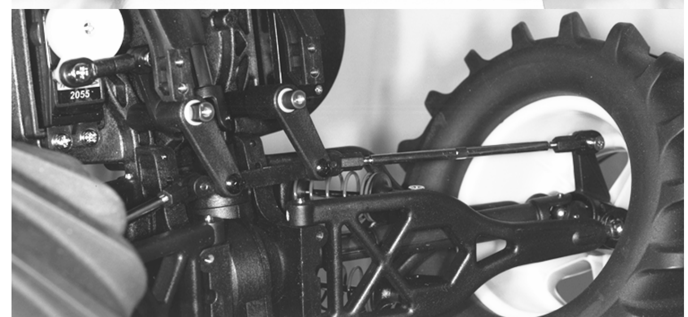


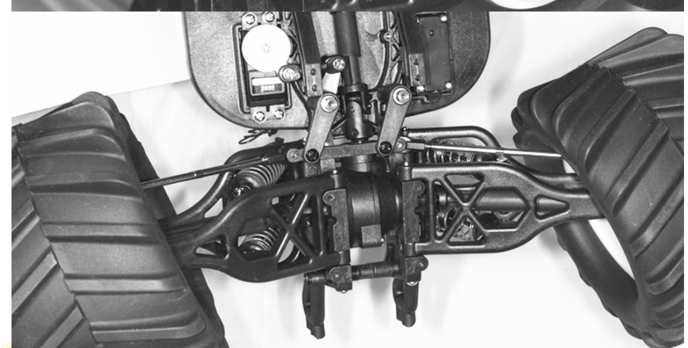
Wheels: *Steering & Suspensions*

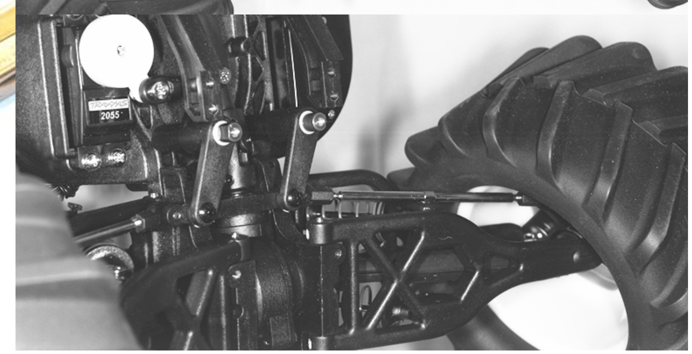
- How to transmit power to the wheels **<u>&</u>** enable them to move with respect to the vehicle to absorb shocks, move across uneven surfaces?
- How to transmit power to the wheels and enable them to steer?
- How does a tractor's suspension work ?
  - Do <u>you</u> really need 4 wheel independent suspension?





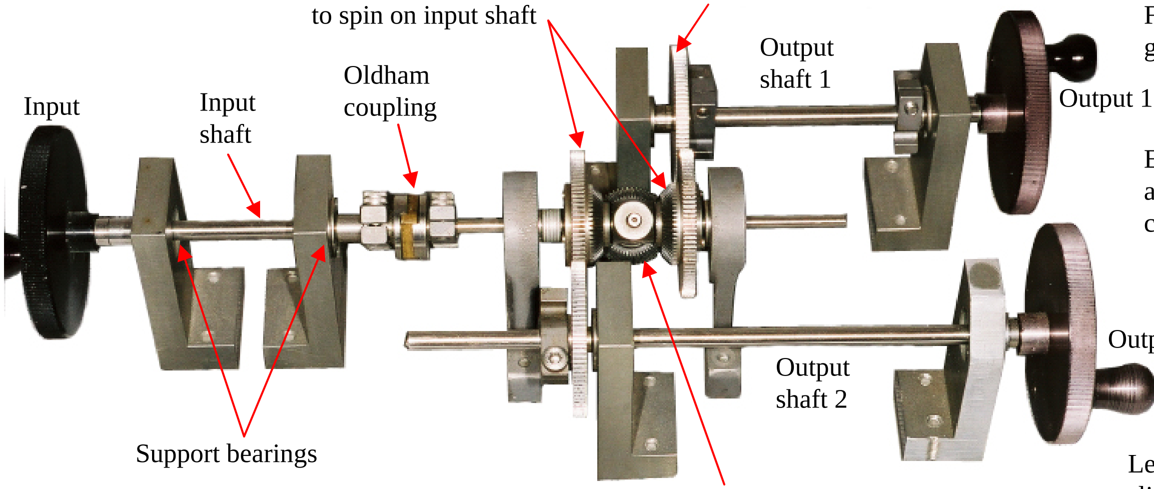




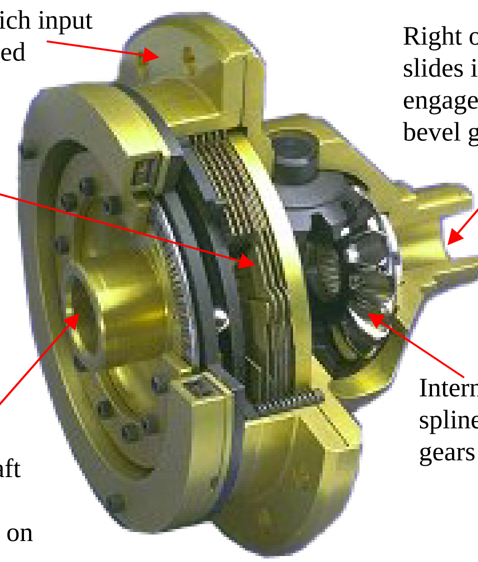


Wheels: *Clutches & Differentials*

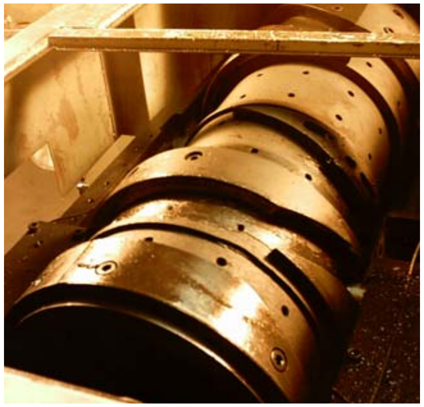
- Clutches and differentials allow for differential velocities between rotating shafts
  - A classic example is when a car makes a turn, all the wheels have the same instant center, but the radius from each wheel to the instant center is different
    - Thus each wheel travels a different distance along an arc in the same time, and a *differential* is needed to enable the speed difference to occur
      - However, if one wheel is on ice, and another wheel is on dry pavement, the wheel on ice will spin
    - Limited slip differentials typically use spring-loaded clutch plates to ensure some torque is always transmitted to both wheels
    - Other designs use a centrifugal force to engage locking features
    - New designs use electromagnetic clutches to optimize torque transfer to the wheels
  - Clutches can be activated mechanically or electrically to control the torque transmitted between shafts, while allowing differential velocity to occur (see page 6-17)



Electric clutch allows limited slip across the differential, or the differential to lock forcing both shafts to be driven. See: http://automotive.eaton.com/product/traction_stability/intellitraxx.html



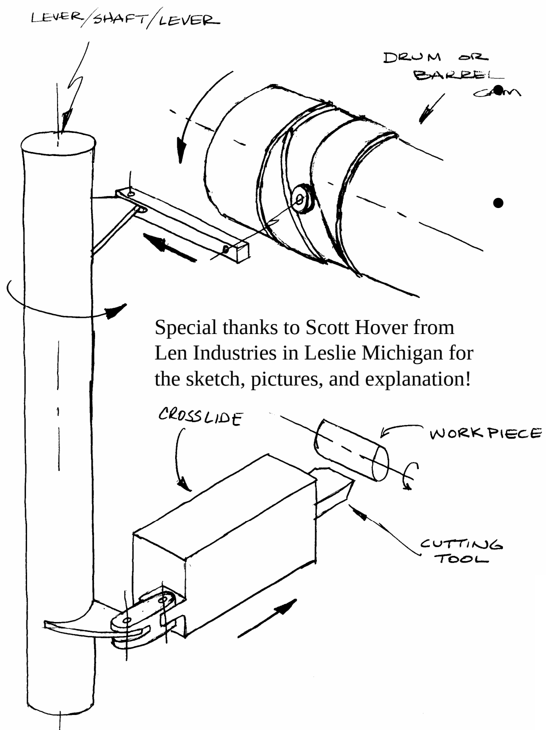
See page 6-19 for a differential a student built for his robot



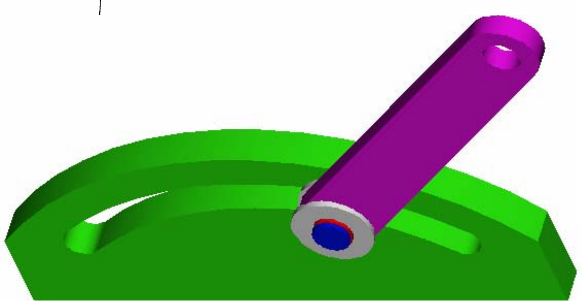
Cams

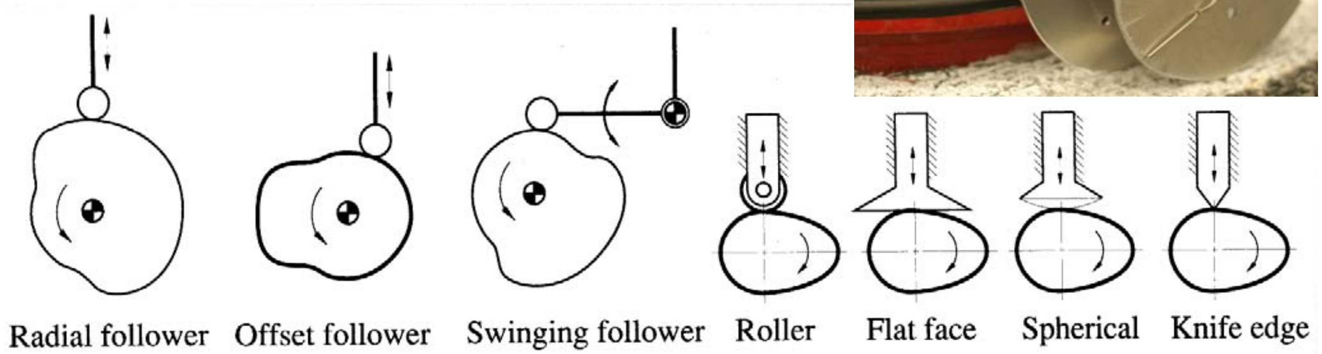
Stanley Tool Works' Yankee™ screwdriver

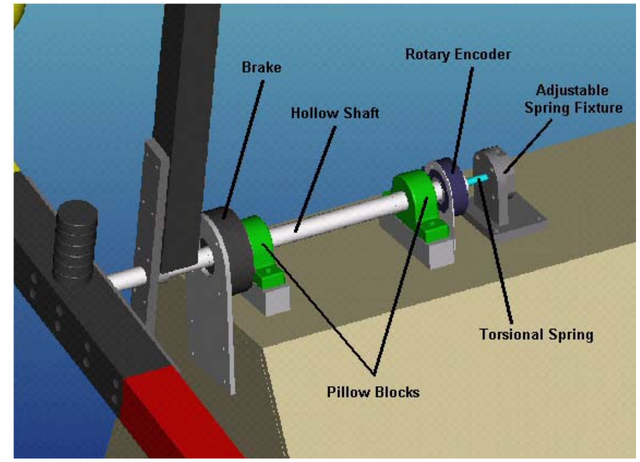
- A *cam* is a rotating shape whose angular motion is converted into output motion by a *cam follower* which rides on the cam surface
  - Rolling elements provide the highest degree of efficiency, but they take up more space
  - Sliding elements are very compact, and can be efficient of the speed is high enough to maintain oil film lubrication
- A *cam follower* is a rolling or sliding contact element that follows the contour of a surface and transmits the motion to a mechanism
- A *cam profile* can be designed to create corresponding *acceleration*, *velocity*, *position*, and *dwell* profiles in a mechanism (e.g., an engine valve)
  - Cam design software can create virtually any type of cam and provide all required engineering data
  - See for example http://www.camnetics.com/



Special thanks to Scott Hover from Len Industries in Leslie Michigan for the sketch, pictures, and explanation!

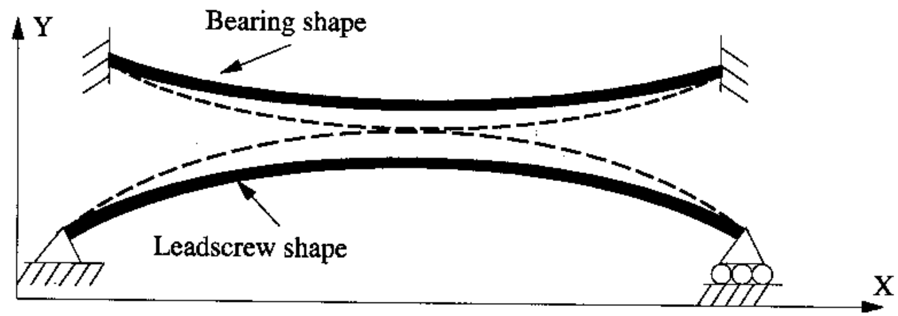




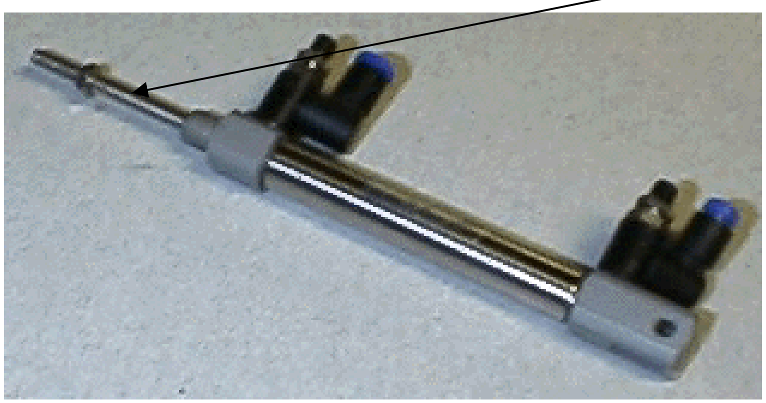


Shafts

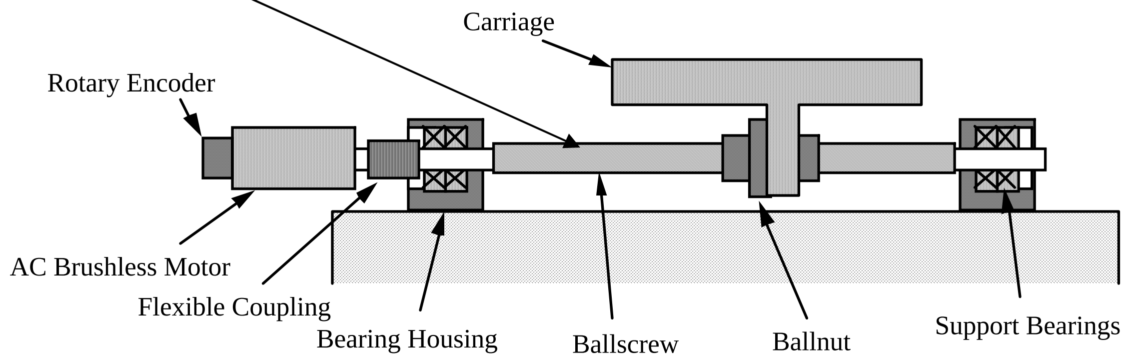
- Shafts transmit rotary and linear power via motors, leadscrews, pistons…
  - Shafts are one of the most common machine elements
- The primary design issues are:
  - Loading conditions and stress concentrations
  - Mounting
  - Component Attachment



Shafts



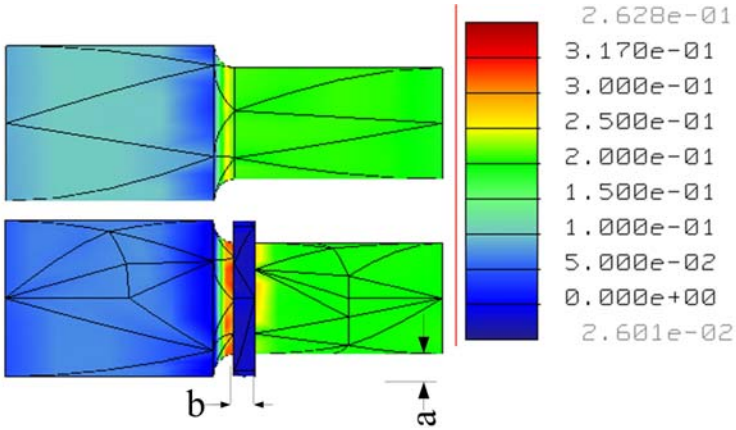
pneumatic or hydraulic cylinder

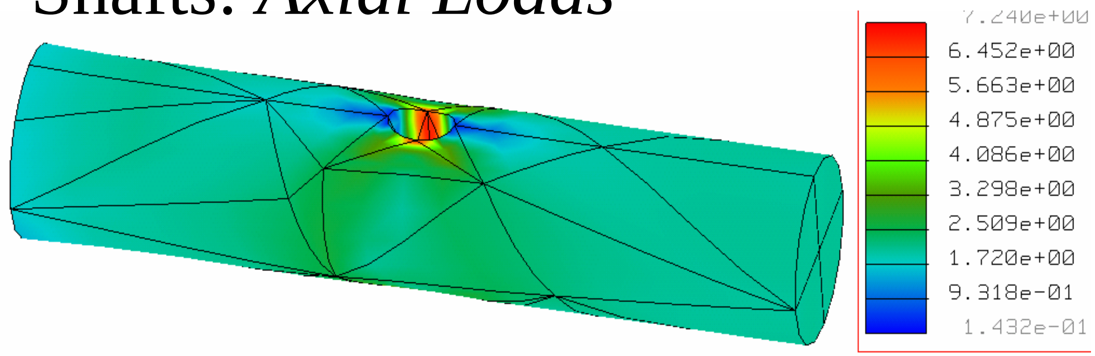


Leadscrew driven carriage

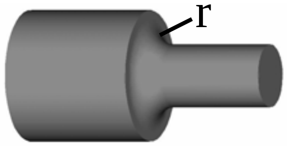
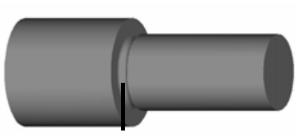
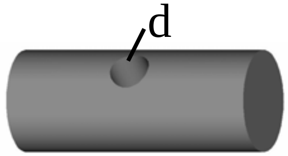
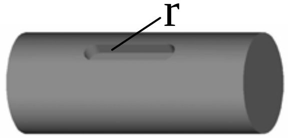
Shafts: *Axial Loads*

See *Shaft_axial.xls*



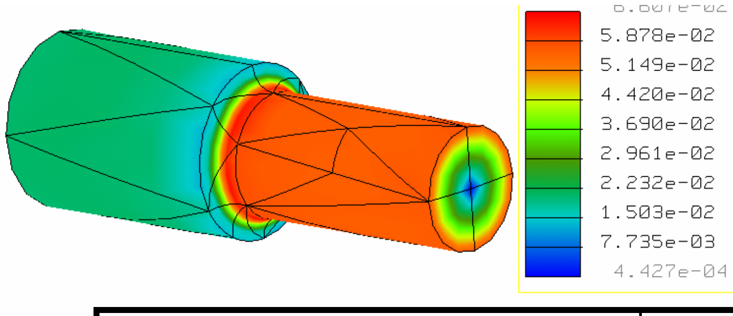


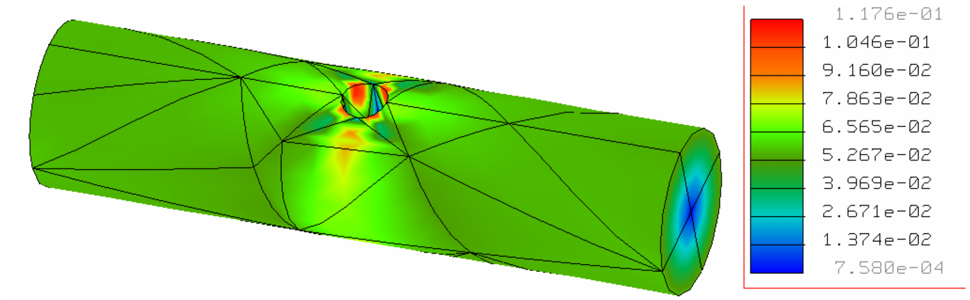
	$K_{t\ radius}/K_{t\ mini\ flange}$		
b/a	axial	torsion	bending
0	1.0	1.0	1.0
0.5	1.2	1.4	1.1
1	1.3	1.4	1.1

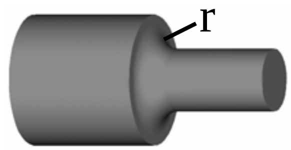
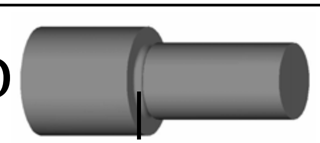
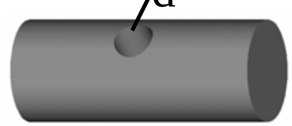
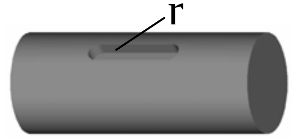
	Shaft loaded by axial force F	Stress	Stress concentration factor
Case 1	D  r d	$\sigma = \frac{K_t 4F}{\pi d^2}$	$K_t = 1 + \frac{(r/d)^{-0.36-0.2(D/d)}}{5 + 0.12/(D/d - 1)}$
Case 2	D  r d	$\sigma = \frac{K_t 4F}{\pi (d-2r)^2}$	$K_t = 1 + \frac{(r/d)^{-0.511-0.34(d/(d-2r)-1)}}{3 + 0.507/(d/d-2r-1)^{0.42}}$
Case 3	D  d	$\sigma \approx \frac{K_t F}{0.25\pi D^2 - dD}$	$K_t \approx 1 + 0.65/(d/D)^{0.275}$
Case 4	D  r Corner r Width b Depth t	$\sigma \approx \frac{K_t F}{0.25\pi D^2 - bt}$	$K_t \approx 1.5$ B=D/4, t=D/8

See *Shaft_torsion.xls*

Shafts: *Torsional loads*

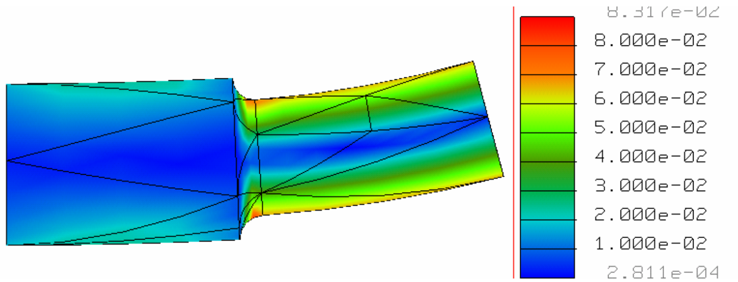


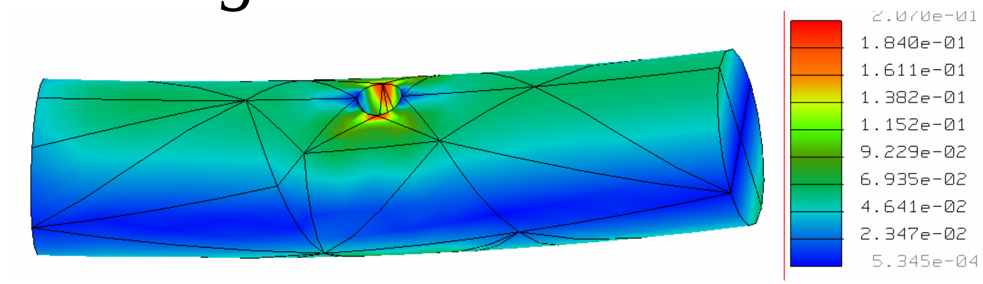


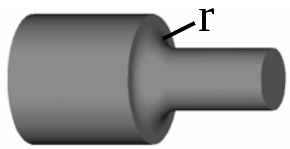
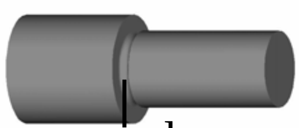
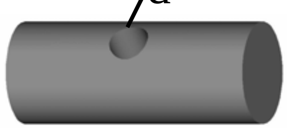
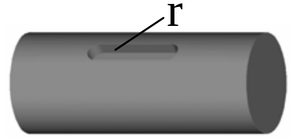
	Shaft loaded by Torque Γ	Stress	Stress concentration factor
Case 1	D  r, d	$\tau = \frac{K_t 16\Gamma}{\pi d^3}$	$K_t = 1 + \frac{(r/d)^{-0.3-0.2(D/d)}}{13 + 0.3/(D/d-1)}$
Case 2	D  r, d	$\tau = \frac{K_t 16\Gamma}{\pi\left(d-2r\right)^3}$	$K_t = 1 + \frac{(r/d)^{-0.609-0.146(d/(d-2r)-1)}}{5 + 3.73/(d/(d-2r)-1)^{0.252}}$
Case 3	D  d	$\tau = \frac{K_t \Gamma}{\pi D^3/16 - d D^2/6}$	$K_t = 1 + 1.47\left(d/D\right)^{-0.197}$
Case 4	D  r Corner r Width b Depth t	$\tau = \frac{K_t 16\Gamma}{\pi D^3}$	$K_t \approx 1.5$ B=D/4, t=D/8

See *Shaft_bending.xls*

Shafts: *Bending Loads*

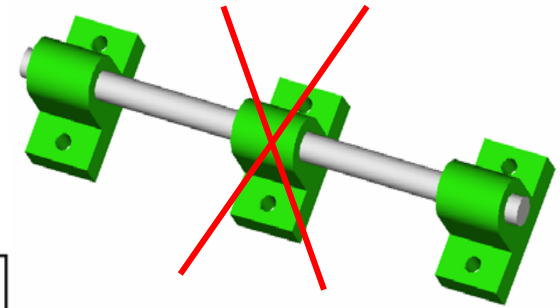




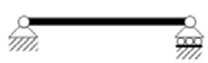
	Shaft loaded by Bending moment M	Stress	Stress concentration factor
Case 1	D  d	$\sigma = \dfrac{K_t 32M}{\pi d^3}$	$K_t = 1 + \dfrac{(r/d)^{-0.73-0.42(D/d-1)}}{5+4.38/(D/d-1)^{0.16}}$
Case 2	D  r, d	$\sigma = \dfrac{K_t 32M}{\pi\left(d-2r\right)^3}$	$K_t = 1 + \dfrac{(r/d)^{-0.59-0.184(d/(d-2r)-1)}}{5+0.081/(d/(d-2r)-1)}$
Case 3	D  d	$\sigma = \dfrac{K_t \Gamma}{\pi D^3/32 - d D^2/6}$	$K_t \approx 1 + 0.65/\left(d/D\right)^{0.275}$
Case 4	D  r Corner r Width b Depth t	$\sigma = \dfrac{K_t 32M}{\pi D^3}$	$K_t = 1 + \dfrac{(r/d)^{-0.66}}{11.14}$ B=D/4, t=D/8

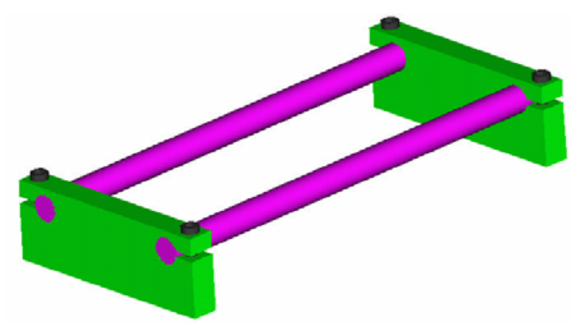
Shafts: *Mounting & Stability*

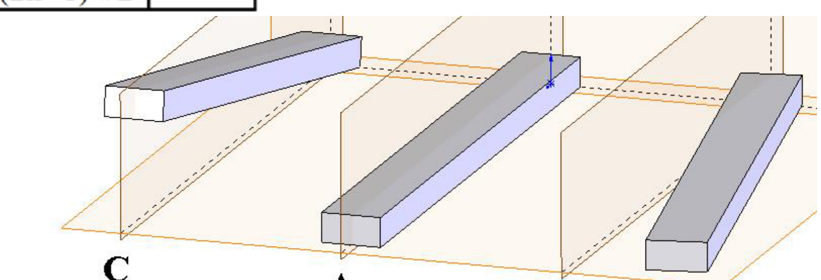
- *Abbe* and *Saint-Venant's* Principles and *Exact Constraint Design* must be carefully considered when designing shaft mountings
- Design the system to accommodate misalignment
  - Allow for clearance between bearing and shaft to accommodate misalignment
  - Use flexible couplings or self-aligning (spherical) bearings
  - Use designs that automatically accommodate misalignment
  - Line-bore holes at the same time through mounting plates



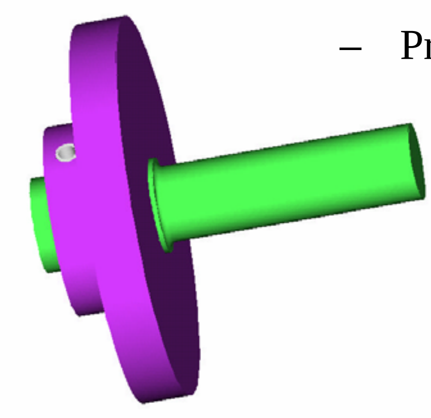
$$\omega_n = k^2\sqrt{\frac{EI}{A\rho L^4}} \qquad F_{\text{Axial buckling}} = \frac{cEI}{L^2} \qquad \Gamma_{\text{Torsional buckling}} = \frac{2\pi E I_P}{L} \quad I_P = \frac{\pi D^4}{32} \quad G = \frac{E}{2(1+\eta)}$$

								
	Cantilevered		Simply Supported		Fixed-Simple		Fixed-Fixed	
mode n	k	c	k	c	k	c	k	c
1	1.875	2.47	3.142	9.87	3.927	20.2	4.730	39.5
2	4.694		6.283		7.069		7.853	
3	7.855		9.425		10.210		10.996	
4	10.996		12.566		13.352		14.137	
n	(2n-1)π/2		nπ		(4n+1)π/4		(2n+1)π/2	

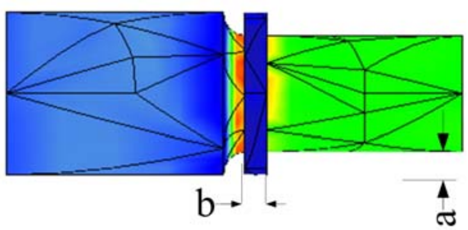




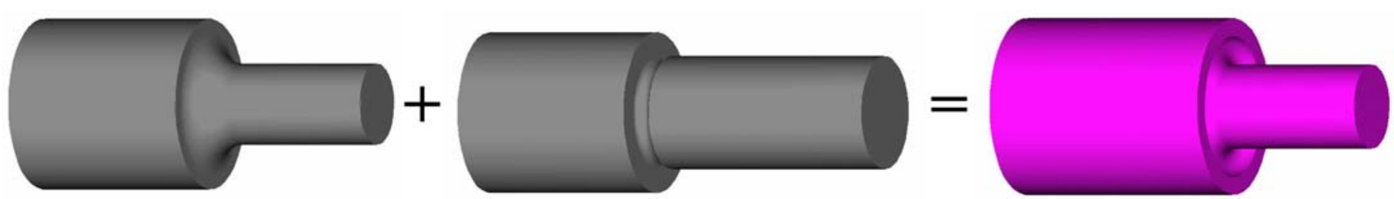
Shafts: *Component Attachment*



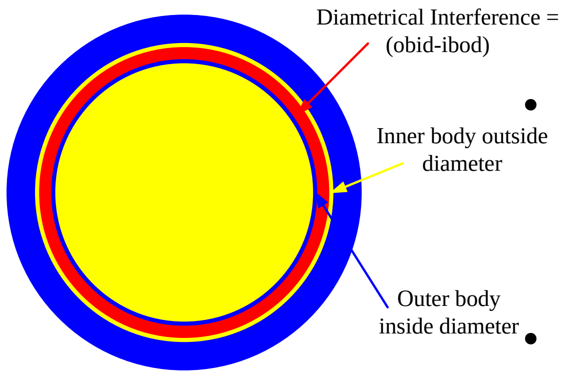
- Principal functional requirements for attaching a component to a shaft:
  - Prevent the component from slipping
    - *Interference-fit:* Best torque transmission, but can be difficult to manufacture
      - A variation is when the shaft and hub are ground to have a mating lobed fit
    - *Spline:* Excellent torque transmission, but can be expensive
    - *Circumferential clamp:* Very good torque transmission, low stress concentration, modest price
    - *Key:* Very good torque transmission, modest stress concentration, low cost
    - *Pinned:* Good torque transmission, modest stress concentration, low cost
    - *Setscrew:* Very low cost, but could be your worst nightmare if it lossens!
  - Minimize stress concentrations
    - Use radiused corners, but be careful of having a square surface for locating components
      - For larger differences in diameters, a radiused undercut can be used
      - For smaller differences in diameters, a small straight flange in front of a radiused corner can be used



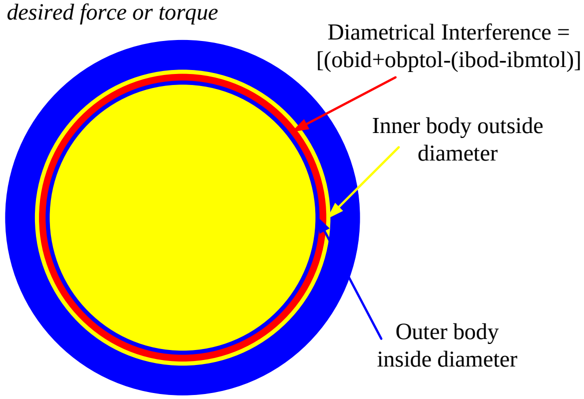
	$K_{t\,radius}/K_{t\,mini\,flange}$		
b/a	axial	torsion	bending
0	1.0	1.0	1.0
0.5	1.2	1.4	1.1
1	1.3	1.4	1.1



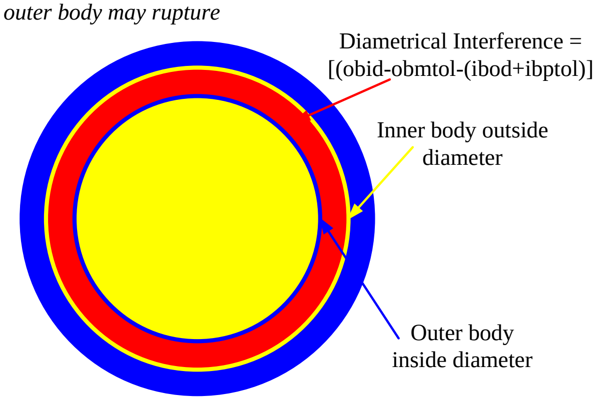
Ideal case



Worst case for loose fit:
Joint may not be able to transmit
desired force or torque



Worst case for tight fit:
Yield stresses may be exceeded and
outer body may rupture

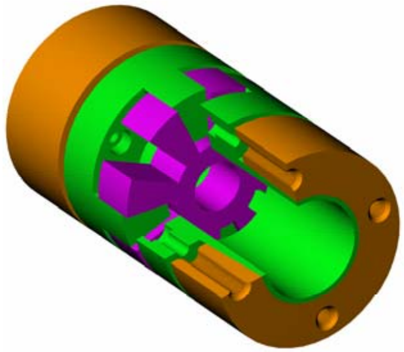


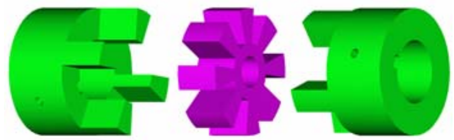
Shafts: *Interference-Fits*

- Interference-fits: most reliable connection:
  - *Joint_interference_fit.xls* models tolerances, differential thermal expansion, and high speed rotation
- Manufacturing issues are of greatest concern
  - Interference is typically small to prevent too high stresses:
    - Radial or circumferential stresses
    - Buckling while pressing in the component
  - Tolerances may cause too high stresses, or too low an interface pressure
  - Clean, high friction interface

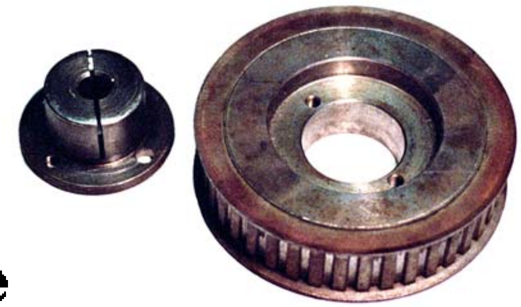
Required interference parameters	
Minimum required interface pressure, rPI (N/mm^2)	**0.8017**
Add Poisson diametral interference, ddp (mm)	**6.92E-06**
Add differential thermal expansion diameter, ted (mm)	**7.50E-04**
Add outer body rotating radial displacement, robd (mm)	**1.80E-06**
Subtract inner body rotating radial displacement, ribd (mm)	**4.17E-07**
Total additional interference amount to be added to ibod, addi (mm)	**0.0008**
Interference fit calculations (assumes addi has been added to ibod)	
maximum interference, maxdelta (mm)	**0.0078**
Maximum resulting interface pressure, maxIP (N/mm^2)	**26.36**
minimum interference, mindelta (mm)	**0.0038**
Minimum resulting interface pressure, minIP (N/mm^2)	**12.77**
Minimum safety margin (min obtained pressure/required pressure)	**15.9**

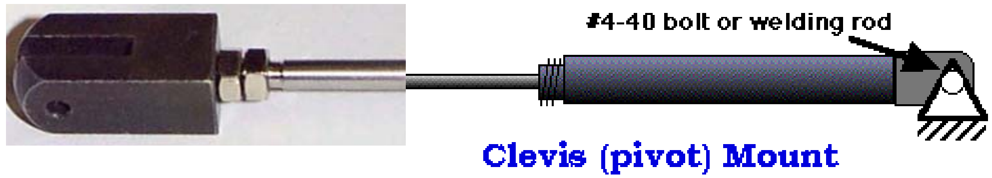
Hexagonal shaft press fit into a plastic wheel's round bore for high torque transmission



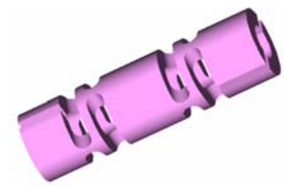


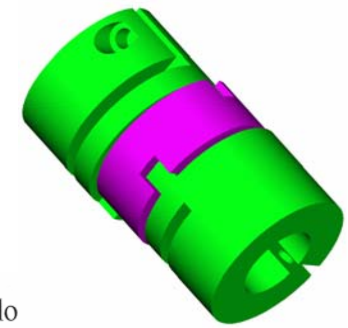
Couplings

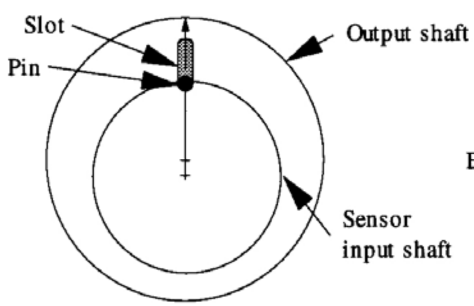


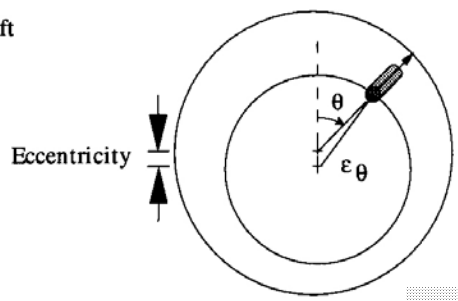


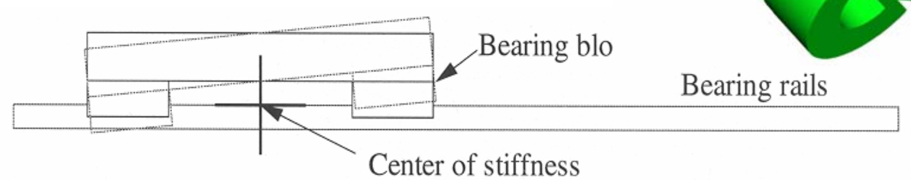
- No two moving components can be perfectly aligned
  - To prevent over constraint from destroying components and robbing your system of power, use couplings
- Identify the degrees of freedom desired, the accuracy (repeatability) needed, and the load capacity and stiffness required in the direction of force or torque transmission
  - Select either a sliding, flexural, or rolling element coupling
  - See Page 10-21 for life calculations

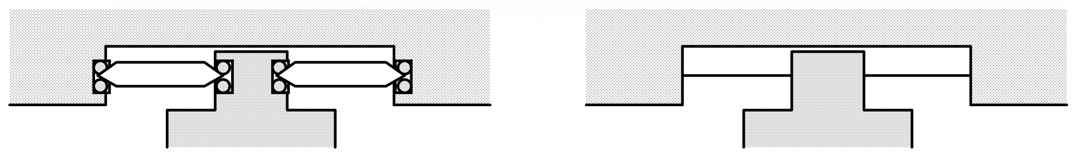


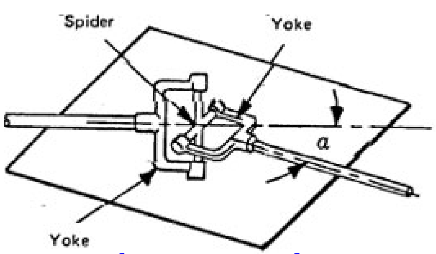


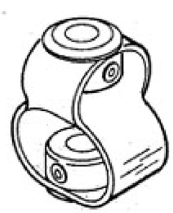


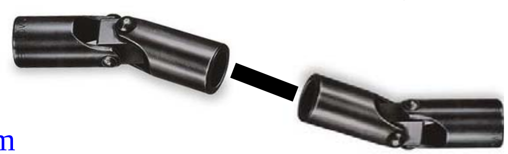




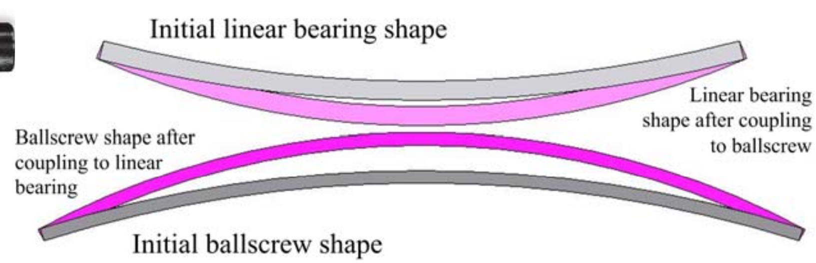


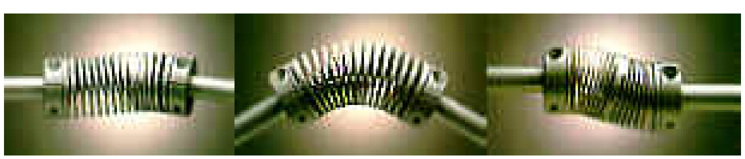






http://www.sdp-si.com/Sdptech_lib.htm

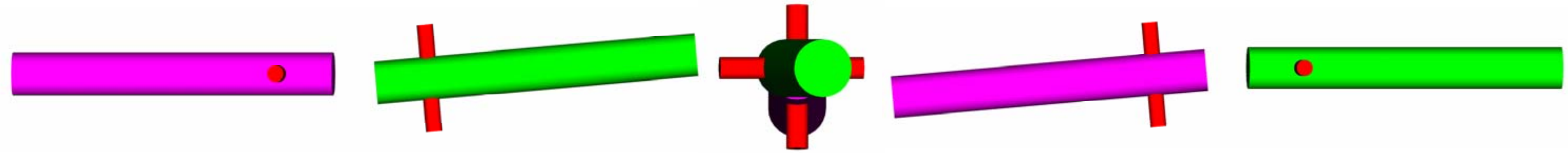




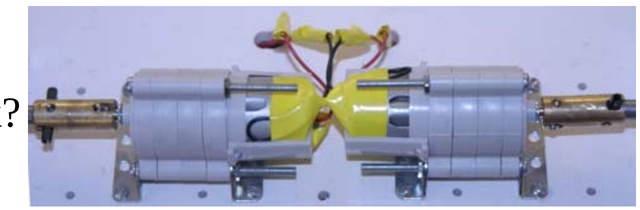
http://www.heli-cal.com/

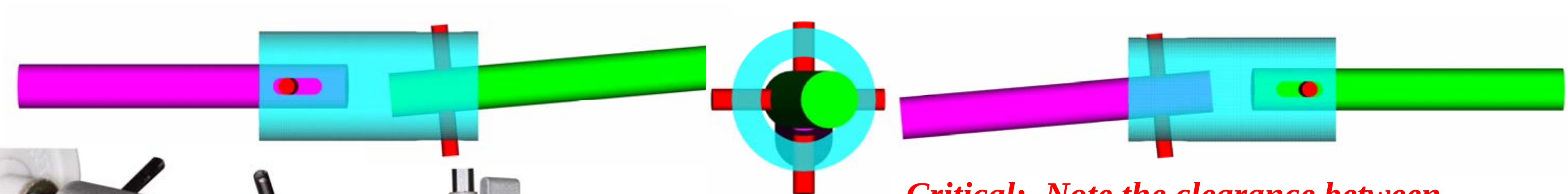
Couplings: *Cheap & Easy Example*

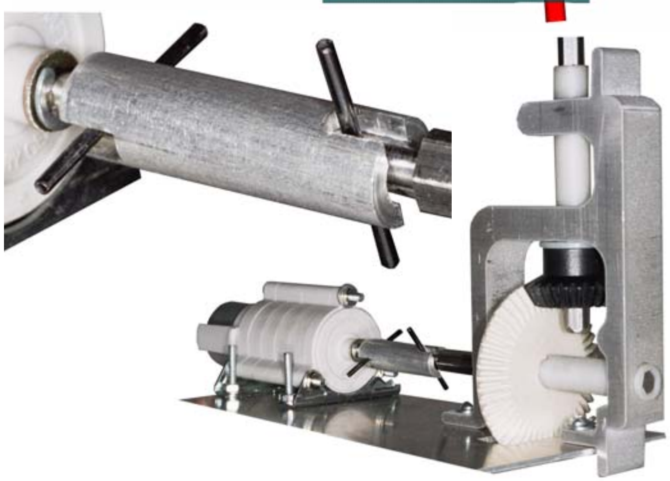
- What about in a robot design contest where two shafts may be linearly misaligned axially, vertically and horizontally, and angularly misaligned?

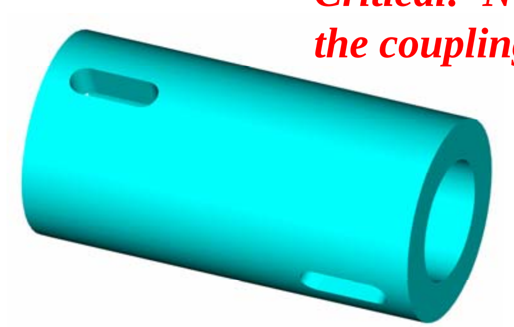


  – How can you design a simple one-piece coupling to enable one shaft to transmit torque to the other shaft?
    - How strong must be the radial pins (*coupling_low_cost.xls*)
    - Can the coupling be made from plastic tube to reduce shock?
    - Would O-rings be useful to nominally center it?









Critical: Note the clearance between the coupling bore and both shafts!