FUNdaMENTALS of Design

Topic 6

Power Transmission Elements II

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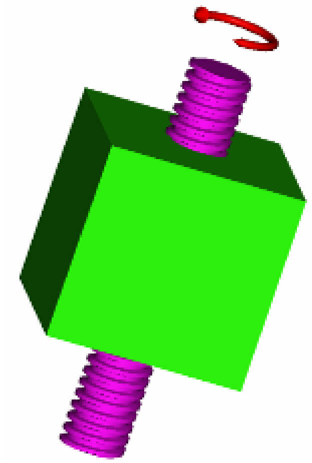
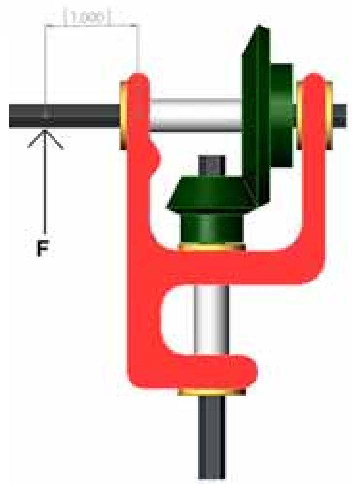


Topics:
- Screws!
- Gears!

www.omax.com

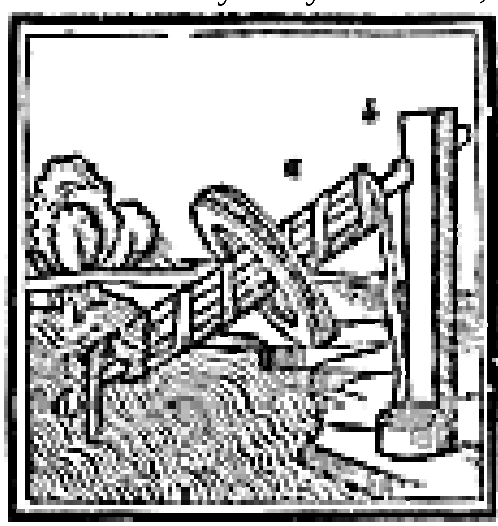


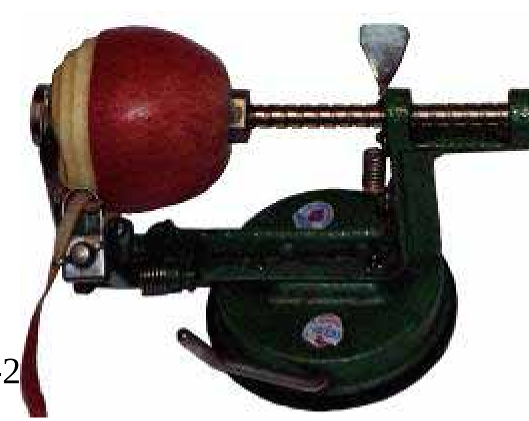
Screws!

- The screw thread is one of the most important inventions ever made
- HUGE forces can be created by screw threads, so they need to be carefully engineered:
  - Leadscrews
  - Physics of operation
  - Stresses
  - Buckling and shaft whip
  - Mounting

- When HUGE forces are created by screws
  - The speed is often slow
  - Always check to make sure you get what you want
  - If you try sometime, you just might get what you need ☺

Mike Schmidt-Lange designed this auger-wheeled vehicle for the “sands” of 1995’s 2.007 contest Pebble Beach, and years later, a major government lab “invented” the idea as a Mars rover sand-propulsion device…

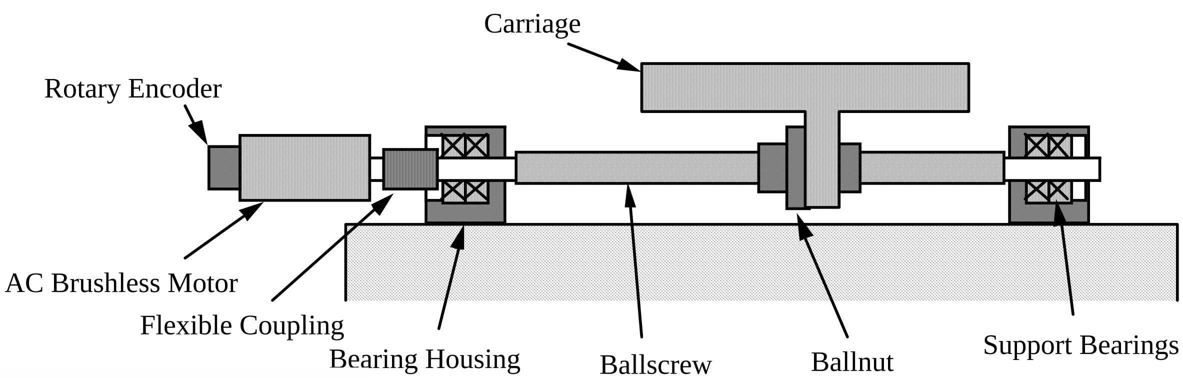


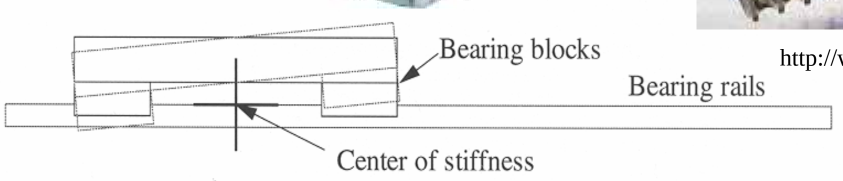


Someday, apples will be so plentiful, people will need machines to peel them…!

Screws: *Leadscrews & Ballscrews*

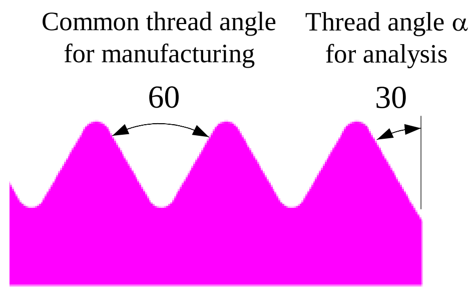
- Leadscrews are essentially accurate screws used to move a nut attached to a load, and they have been used for centuries to convert rotary motion into linear motion
  - *Leadscrews* are commonly used on rugged economy machine tools
  - Efficiency in a leadscrew system may be 30-50%,
- Precision machine or those concerned with high efficiency often uses a *ballscrew*
  - Sliding contact between the screw and nut is replaced by recirculating ball bearings and may have 95% efficiency



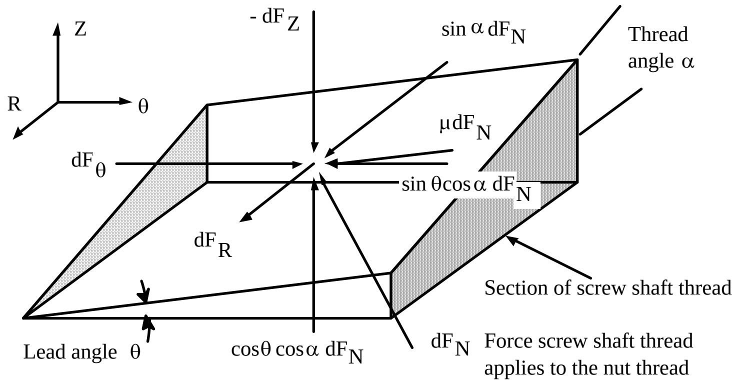


http://www.thomsonindustries.com/industrl/ti090600.htm

Screws: *Forces*



- To move a load with a screw thread:



$$\beta = \ell / D_{pitch}$$

$$\eta_{raise} = \frac{\left(\cos\alpha - \mu\beta/\pi\right)}{\left(\cos\alpha + \pi\mu/\beta\right)}$$

$$\eta_{lower} = \frac{\left(\cos\alpha + \mu\beta/\pi\right)}{\left(\pi\mu/\beta - \cos\alpha\right)}$$

  – Γ is the applied torque
  – μ is the coefficient of friction (0.1 typical for greased threads)
  – D_{pitch} is the pitch diameter of the screw thread
  – ℓ is the lead of the thread (e.g., mm/revolution)
  – D is the bolt head or thrust bearing diameter
  – α is the thread angle (typically 30 degrees for a standard bolt)

Screwforce.xls		
Spreadsheet for lifting force from a screw		
Written 3/08/01 by Alex Slocum		
Enter numbers in bold		
Be consistant with units! (in, lb or N, m or N, mm)		
Motor torque (input)	**50**	
Motor speed (rpm)	**100**	
Dthrustbearing	**12**	
Dpitch	**5**	
Lead	**1.25**	
alpha, cos(alpha)	**30**	0.8660254
Coefficients of friction		
muthrustbearing	**0.2**	
muthreads	**0.2**	
beta	**0.25**	
To RAISE a load		
screwthread efficiency, etaraise	**25.16%**	
Without thrust bearing		
Force (output)	**63.2**	
With thrust bearing		
Force (output)	**25.1**	
Linear speed (mm/sec)	**2.08**	
To LOWER a load		
screwthread efficiency, etalower	**54%**	
Without thrust bearing		
Force (output)	**134.6**	
With thrust bearing		
Force (output)	**31.8**	

- Based on a simple work-in=work-out (torque*one rev=Force*lead (distance/rev) with efficiency of η:

$$\eta_{\text{thrust}} = \frac{\ell}{\ell + \pi\eta_{\text{thread}}\mu D_{\text{mean diameter thrust bearing}}}$$

$$\Gamma_{\text{required}} = \frac{F_{\text{desired}}\ell}{2\pi\eta_{\text{thread}}} + \frac{F_{\text{desired}}\mu D_{\text{mean diameter thrust bearing}}}{2} = \frac{F_{\text{desired}}\ell}{2\pi\eta_{\text{thread}}\eta_{\text{thrust}}}$$

Screws: *Stresses*

- Forces generated by screw threads creates tension & torsion
  - The thread root is a stress concentration area (on the order of 1.5)
  - The stresses, not including the stress concentration, are:

$$\sigma_{tensile} = \frac{4F_{axial}}{\pi D^2_{root\_diameter}} \qquad \tau_{shear} = \frac{16F_{axial}}{\pi D^3_{root\_diameter}}$$

- The Von Mises equivalent stress is:

$$\sigma_{tensileequivelent} = \sqrt{\sigma^2_{tensile} + 3\tau^2_{shear}}$$

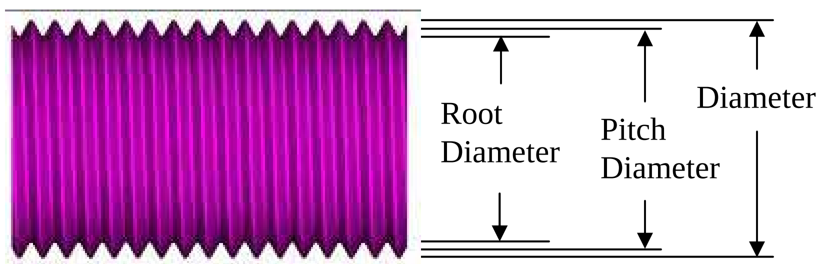
- Minimum thread engagement length to avoid shearing:

$$F_{Shear\_Nut\_Threads} = F_{Bolt\_Tensile}$$

$$\left(\frac{L_{Nut}}{2}\right)\pi\left(\frac{D_{Thread\_outside\_diameter} + D_{Thread\_root\_diameter}}{2}\right)\left(\frac{\sigma_{yield}}{2}\right) = \frac{\pi D^2_{Thread\_root\_diameter}\sigma_{yield}}{4}$$

$$L_{Nut} \approx D_{Bolt}$$

leadscrew_design.xls		
Screwthread forces		
Enter numbers in BOLD, output in RED		
Written by Alex Slocum, last updated 1/17/03		
Force (no help from gravity), thrust (N)	**400**	
Lead, (mm)	**2**	
Coefficient of friction, mu	**0.1**	
Screw pitch diameter, dscrew (mm)	**20**	
Thrust bearing diameter, dthrust (mm)	**25**	
Thread angle (deg), alpha (rad)	**30**	0.524
Thread root stress concentration, scf	**1.5**	
Beta	0.1	
Torque required at screw, gamscrew (N-mm)	591	
Torque required at thrust bearing, gamthrust(N-mm)	500	
Thrust bearing efficiency, etathrust	54%	
Total torque, gamtotal (N-mm)	1,091	
Backdriveable?	NO	
Thread efficiency, et	22%	
Total system efficiency, eta	12%	
Estimated torsional stress, tau (N/mm^2)	0.52	
Tensile stress, sig (N/mm^2)	1.57	
Mises equivelant stress, sigma (N/mm^2)	2.71	
Gearbox ratio, n	**1**	
Travel, s (mm)	**50**	
Time to travel, tt (s)	**5**	
Motor speed, w (rpm, rad/s)	300	31
Gearbox efficiency, etagearbox	**90%**	
Motor torque, gammotor (N-mm)	1213	
Power, Preq (watts)	38	

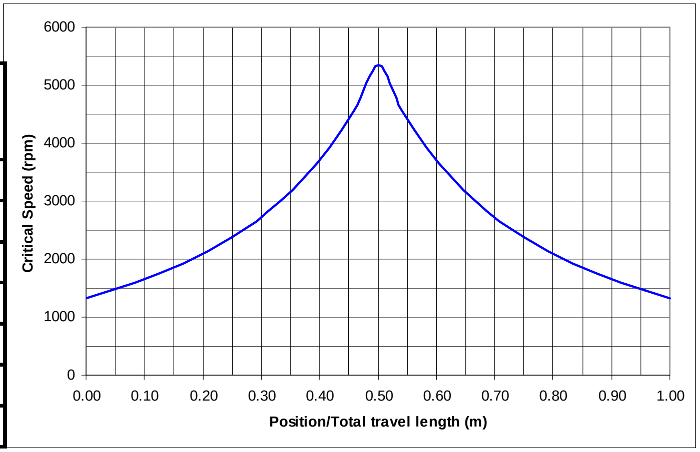


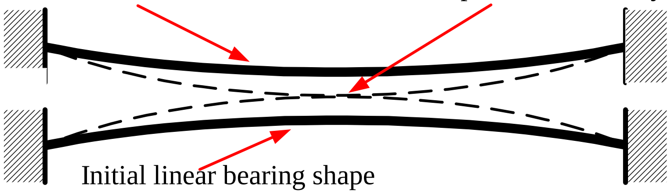
Leadscrews: *Buckling and Shaft Whip*

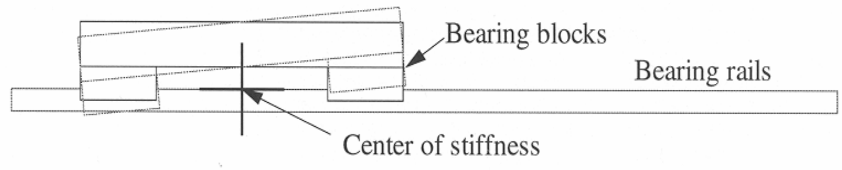
- Leadscrews in compression can *buckle*
  - Pull on a straw and it slips out of your hands
  - Push on a straw and it will “snap in half”
    - *Buckling* is a common failure mode in shafts
    - If possible, put shafts in TENSION and avoid the problem!
  - Leadscrews can easily generate forces that will make them buckle
    - Heavily loaded leadscrews should ideally be used to ***PULL*** not ***PUSH*** loads!
    - The calculations are EASY, DO THEM! (use the ROOT diameter and mks units!)
  - Thermal expansion in precision systems can be overcome by pre-stretching a screw
- Leadscrews that spin too fast can excite shaft bending, *shaft whip*, and cause support bearing failure

$$\omega_n = k^2\sqrt{\frac{EI}{\rho L^4}} \qquad F_{buckle} = \frac{cEI}{L^2}$$

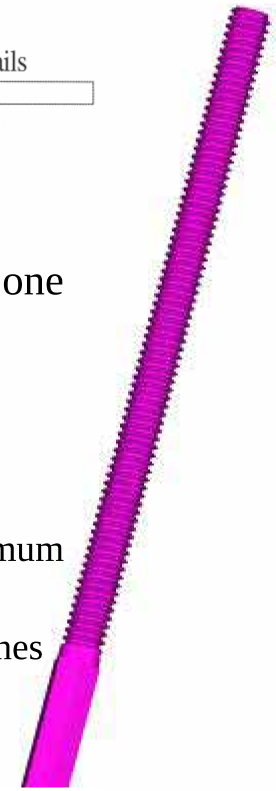
								
	Cantilevered		Simply Supported		Fixed-Simple		Fixed-Fixed	
mode n	k	c	k	c	k	c	k	c
1	1.875	2.47	3.142	9.87	3.927	20.2	4.730	39.5
2	4.694		6.283		7.069		7.853	
3	7.855		9.425		10.210		10.996	
4	10.996		12.566		13.352		14.137	
n	(2n-1)π/2		nπ		(4n+1)π/4		(2n+1)π/2	



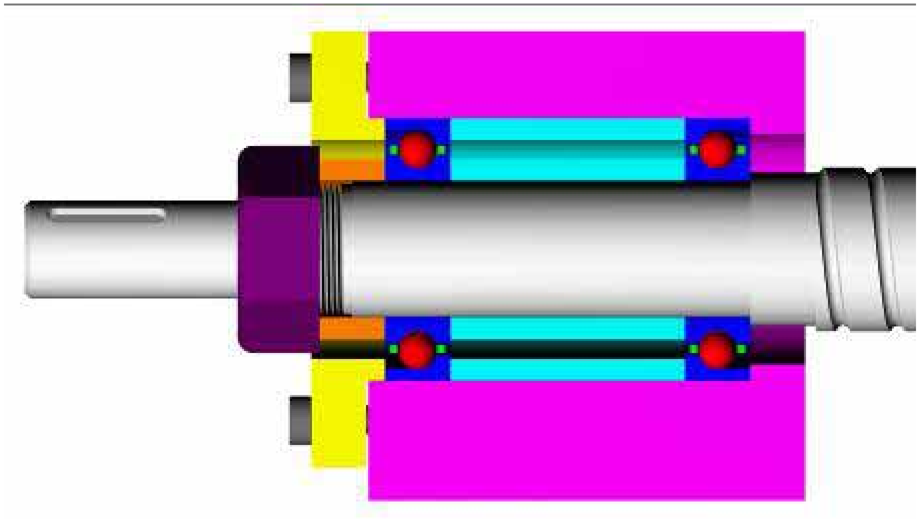


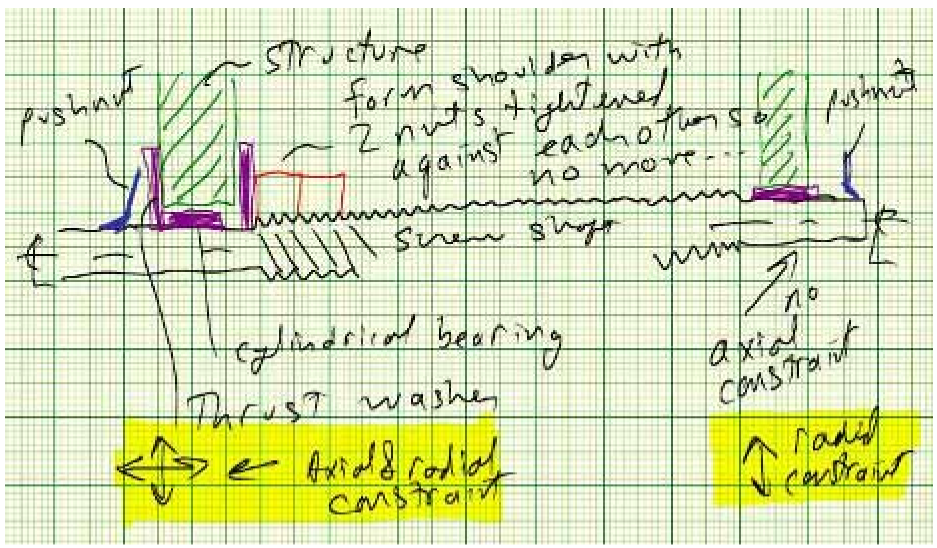


Leadscrews: *Mounting*



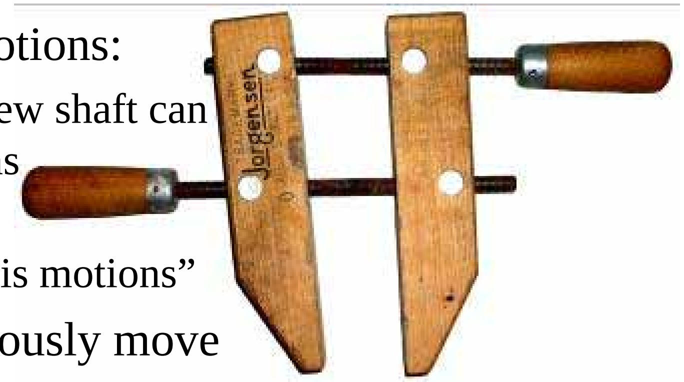
- Leadscrews used in robotics contests are often mounted using a radial sleeve bearing at one end, and journal and thrust bearings at the other end
  - The bearings in gear motors are generally not designed to take the huge thrust loads that a leadscrew can generate
- Beware of constraints: either provide precision or compliance
  - The only way to effectively mount a leadscrew to achieve a zero-slope end condition for maximum buckling resistance is to use a back-to-back arrangement of ball bearings
    - This also generally involves the use of a ballscrew and is not used in simple 2.007 machines
- It is easy to make a leadscrew
  - Screw threads can be cut directly into round, square, or hexagonal steel stock
    - A square or hexagonal hole can be broached into a gear or pulley which can then be pressed onto the leadscrew



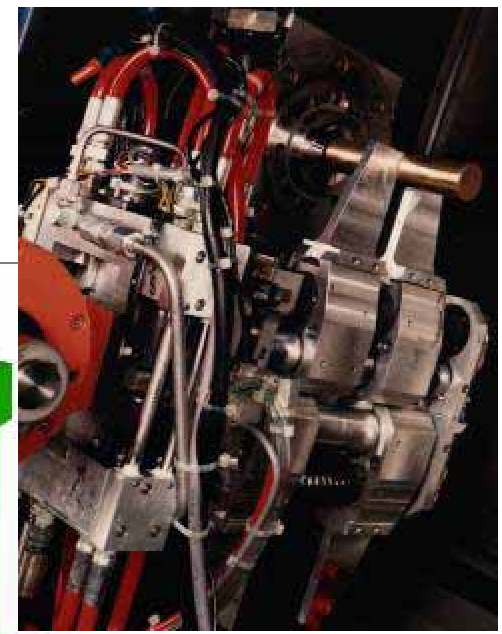


Leadscrews: *Differential Motion*

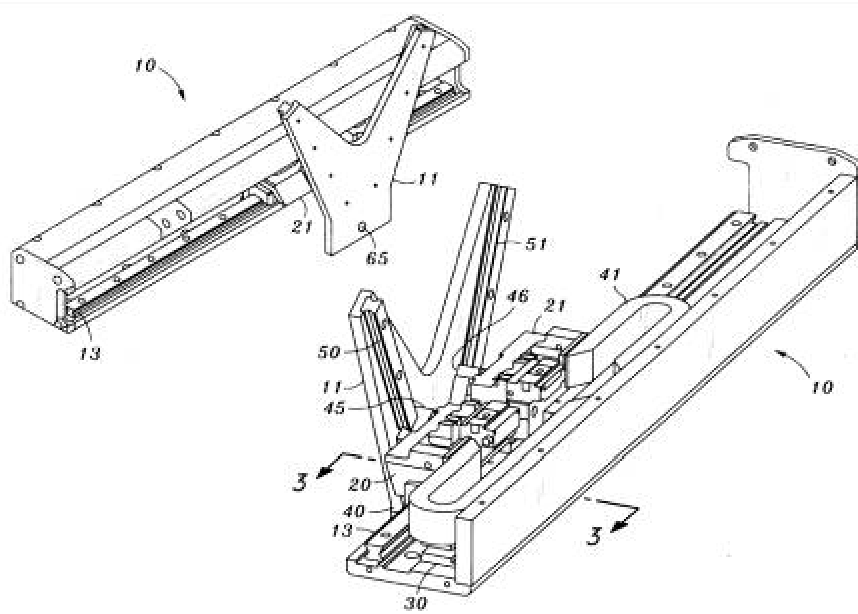
- Differential motion can be used to create most excellent motions:
  - Two independently rotating leadscrew nuts on a common screw shaft can enable components to move in the same or different directions simultaneously
    - See US patent **6,194,859** “X-Y positioner based on X axis motions”
- A leadscrew with left and right hand threads can simultaneously move components together or apart
  - See US patent 4,765,668 " Double End Effecter“
- A leadscrew with two different leads can create an incredibly small virtual lead



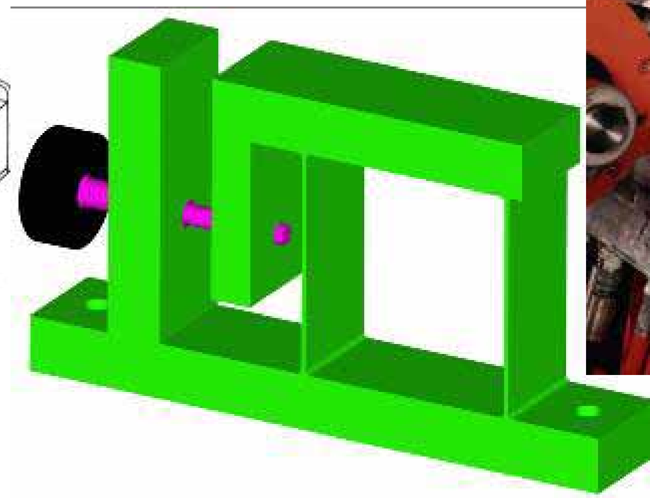
♥ Alex Slocum’s first miniature 6 axis robot and double gripper! ♥



Note the gripper’s left/right hand screws that actuate the fingers. Where did he get the idea?

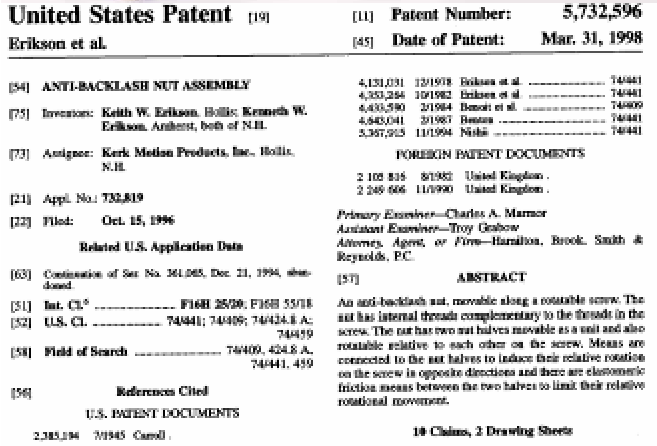


How do you get the screw in?!



Leadscrews: *Preload*

- Threads can never mate perfectly: *backlash* normally exists
  - When a screw is rotated in one direction, the nut translates
  - When rotation stops and reverses direction, for a small angle there is no translation of the nut (backlash or lost motion)
- Preload is used to remove the backlash
  - Both sides of the threads are loaded with some sort of spring to removed backlash
- Preloading is used for ballscrews and leadscrews and many other relative motion machine elements (see page 10-16)



United States Patent [19]
Erikson et al.

[11] **Patent Number:** 5,732,596
[45] **Date of Patent:** Mar. 31, 1998

[54] **ANTI-BACKLASH NUT ASSEMBLY**

[75] Inventors: **Keith W. Erikson**, Hollis; **Kenneth W. Erikson**, Amherst, both of N.H.

[73] Assignee: **Kerk Motion Products, Inc.**, Hollis, N.H.

[21] Appl. No.: **732,819**

[22] Filed: **Oct. 15, 1996**

Related U.S. Application Data

[63] Continuation of Ser. No. 361,065, Dec. 21, 1994, abandoned.

[51] **Int. Cl.**[6] **F16H 25/20**; F16H 55/18
[52] **U.S. Cl.** .... **74/441**; 74/409; 74/424.8 A; 74/459
[58] **Field of Search** .... 74/409, 424.8 A, 74/441, 459

[56] **References Cited**

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5,367,915	11/1994	Nishi	74/441

FOREIGN PATENT DOCUMENTS

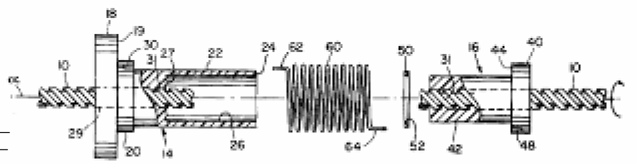
2 105 816	8/1982	United Kingdom .
2 249 606	11/1990	United Kingdom .

Primary Examiner—Charles A. Marmor
Assistant Examiner—Troy Grabow
Attorney, Agent, or Firm—Hamilton, Brook, Smith & Reynolds, P.C.

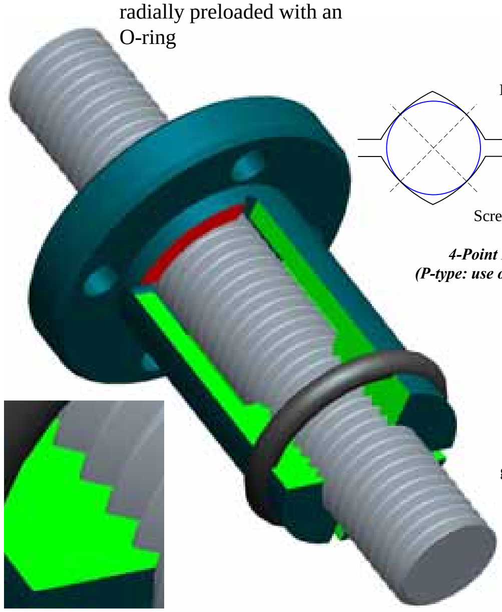
[57] **ABSTRACT**

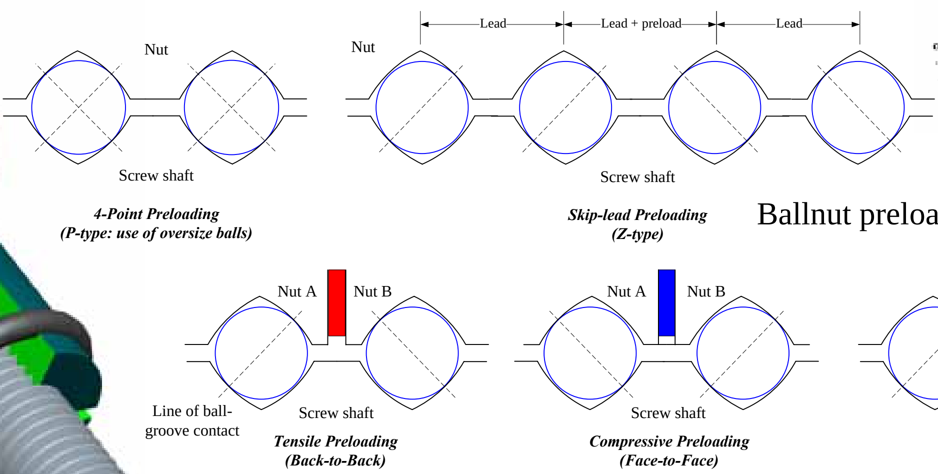
An anti-backlash nut, movable along a rotatable screw. The nut has internal threads complementary to the threads in the screw. The nut has two nut halves movable as a unit and also rotatable relative to each other on the screw. Means are connected to the nut halves to induce their relative rotation on the screw in opposite directions and there are elastomeric friction means between the two halves to limit their relative rotational movement.

10 Claims, 2 Drawing Sheets



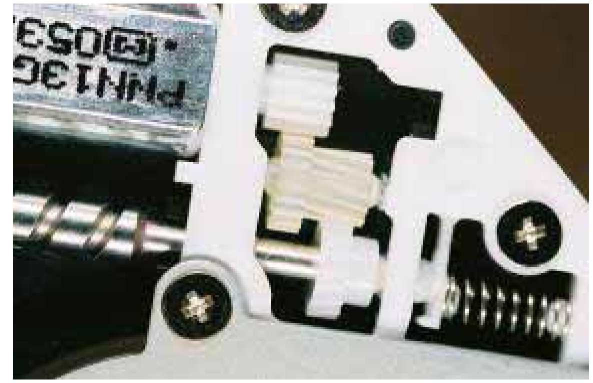
A plastic nut can be axially slit and then the threads radially preloaded with an O-ring





Ballnut preload methods

Leadscrews: *Flexibility*



- Leadscrews are used in many everyday applications
  - How does a CD drive work?
- Must the pitch of a leadscrew be constant?
  - See “Expanding Gripper with Elastically Variable Pitch Screw”, #5,839,769, Nov. 24, 1998

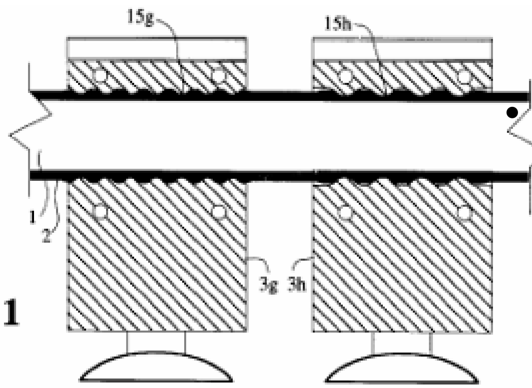


Fig. 1

To reduce friction, could the gripper units’ threads be replaced with inclined rollers at different angles to achieve different effective leads? (I bet they could!)

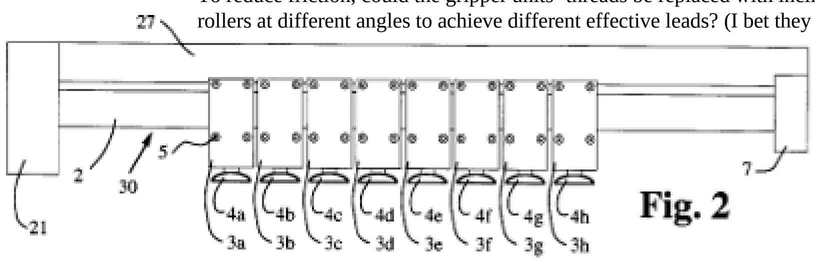


Fig. 2

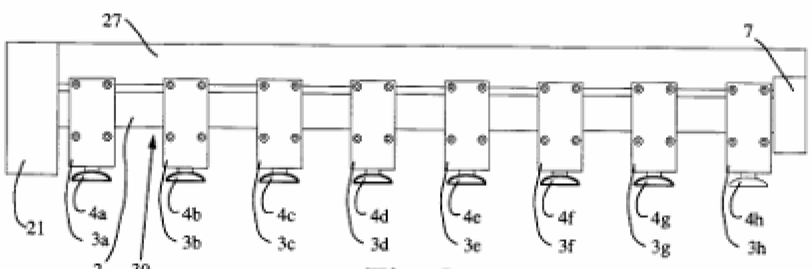
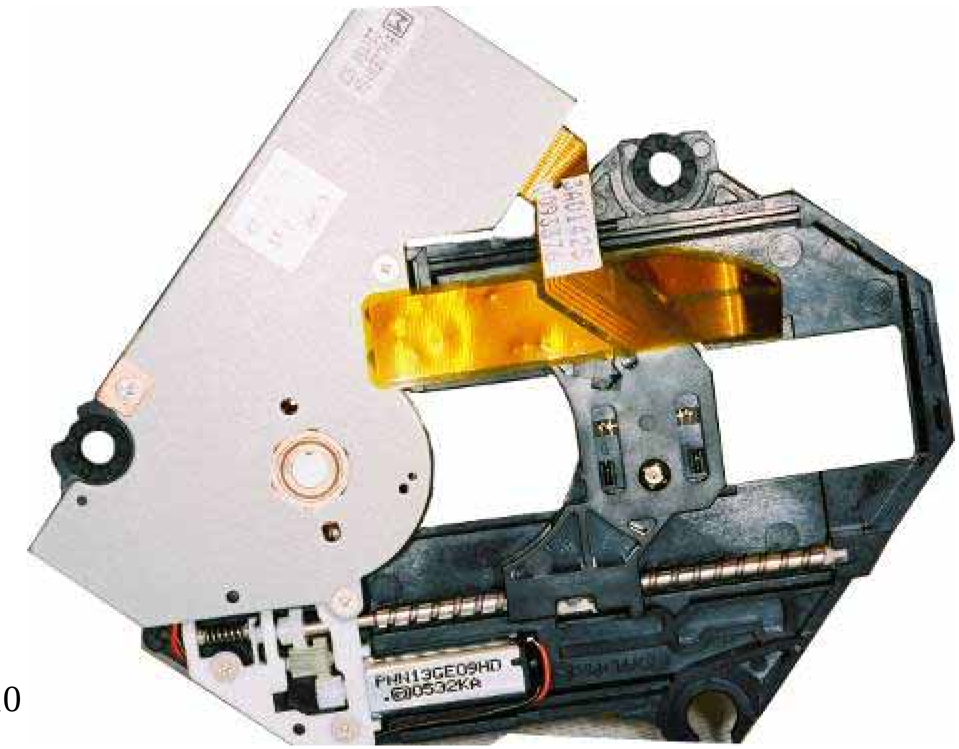
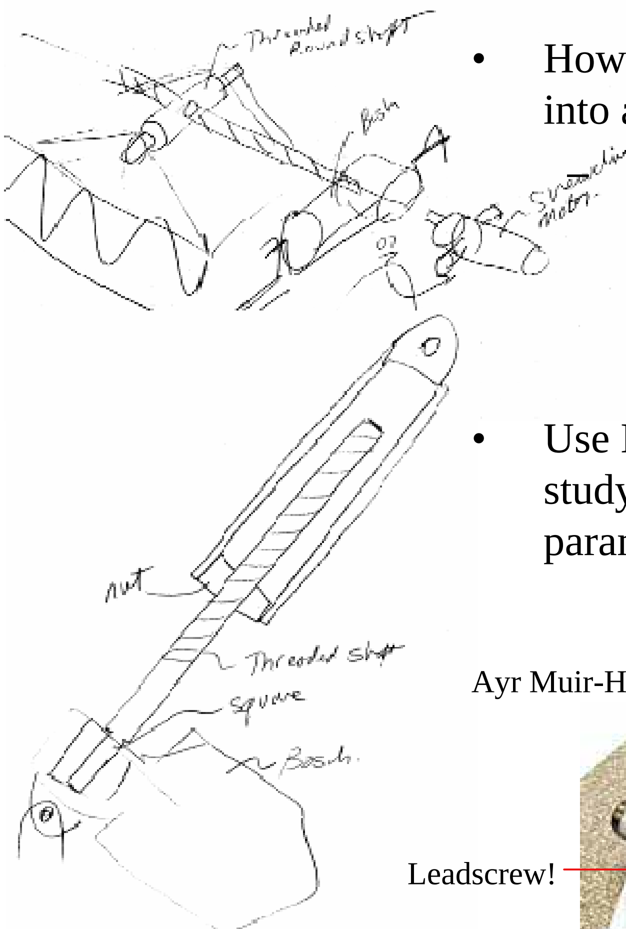


Fig. 3



Leadscrews: *Contest Machine Design Example*



- How might we evolve a lifting strategy into a boom concept?
  - What are the forces on the boom and where are they applied? What are its ranges of motion? How fast should it move the load? What is the desired resolution of motion?
- Use Matlab™ or a spreadsheet to study the effects of different design parameters?

leadscrew_design.xls		
Screwthread forces		
Enter numbers in BOLD, output in RED		
Written by Alex Slocum, last updated 1/17/03		
Force (no help from gravity), thrust (N)	**400**	
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Coefficient of friction, mu	**0.1**	
Screw pitch diameter, dscrew (mm)	**20**	
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Torque required at thrust bearing (N-mm)	500	
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Tensile stress (N/mm^2)	1.57	
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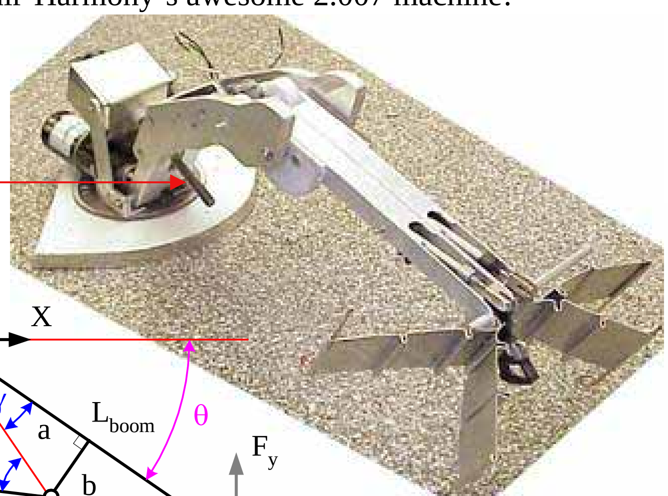
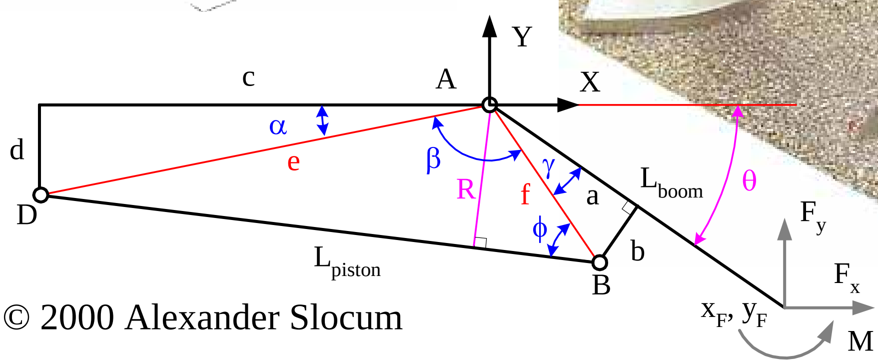
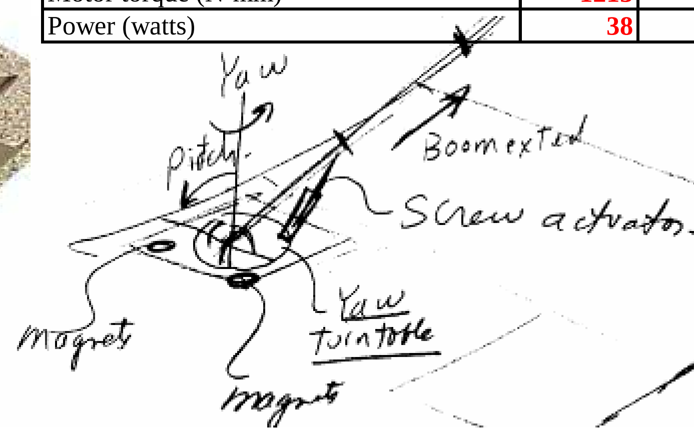
Travel (mm)	**50**	
Time to travel (s)	**5**	
Motor speed (rpm, rad/s)	300	31
Gearbox efficiency	**90%**	
Motor torque (N-mm)	1213	
Power (watts)	38	

Ayr Muir-Harmony's awesome 2.007 machine!

Leadscrew!



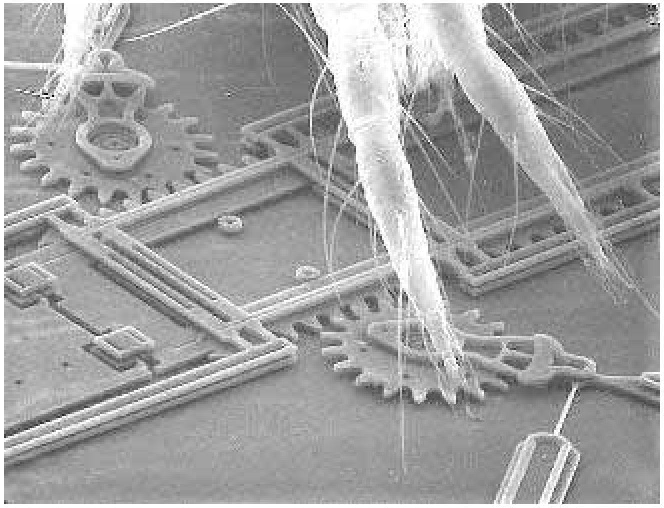


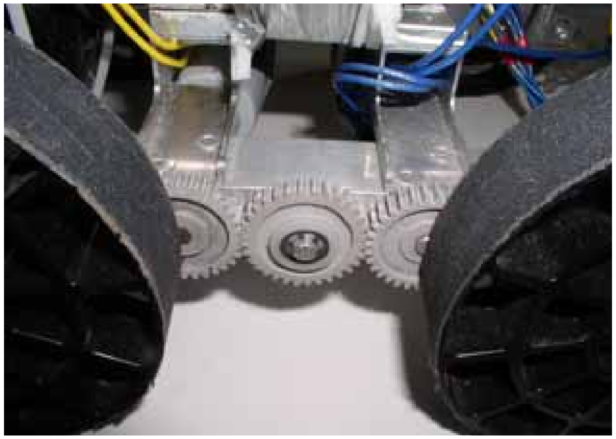


Gears!

- Gears are most often used in transmissions to convert an electric motor's high speed and low torque to a shaft's requirements for low speed high torque:
  - *Speed* is easy to generate, because voltage is easy to generate
  - *Torque* is difficult to generate because it requires large amounts of current
- Gears essentially allow positive engagement between teeth so high forces can be transmitted while still undergoing essentially rolling contact
  - Gears do not depend on friction and do best when friction is minimized
- Basic Law of Gearing:
  - *A common normal (the line of action) to the tooth profiles at their point of contact must, in all positions of the contacting teeth, pass through a fixed point on the line-of-centers called the pitch point*
  - Any two curves or profiles engaging each other and satisfying the law of gearing are *conjugate curves, and the relative rotation speed of the gears will be constant*

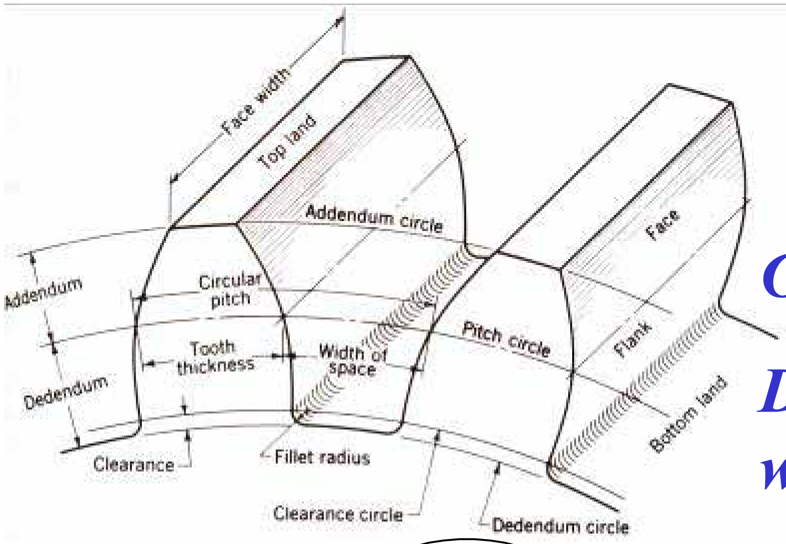
http://mems.sandia.gov/scripts/images.asp

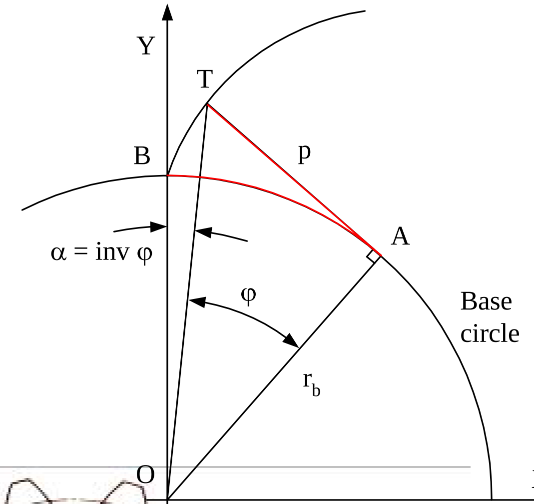




http://www.bostongear.com/

Gears: *Involutes*



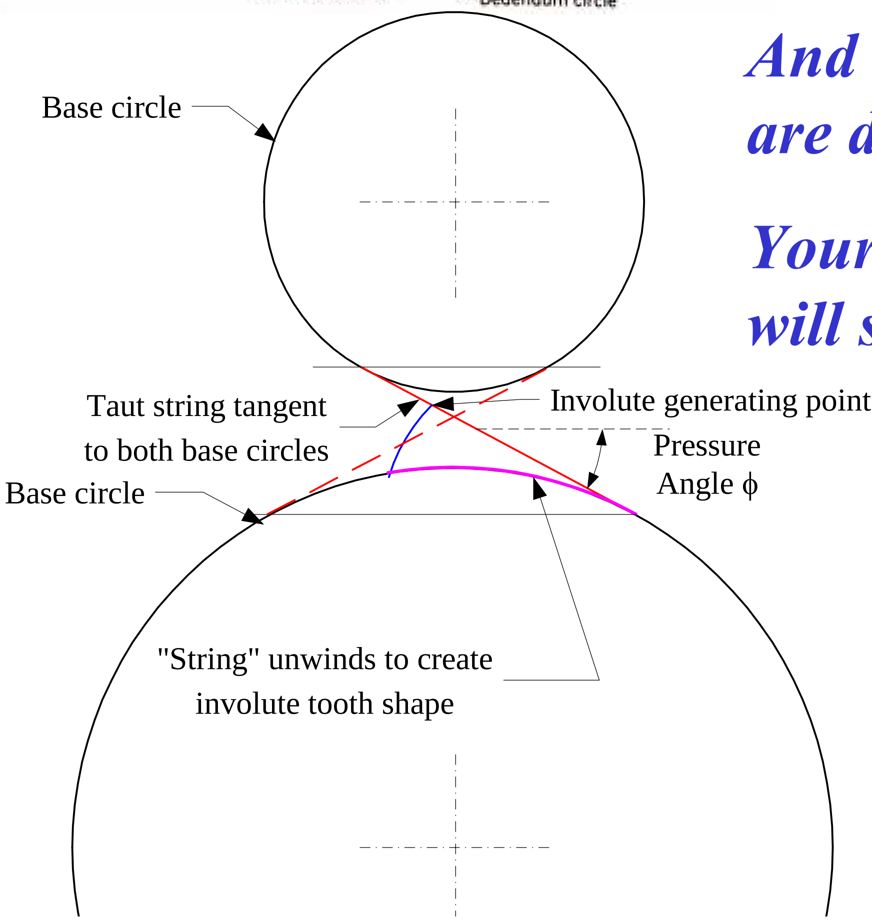


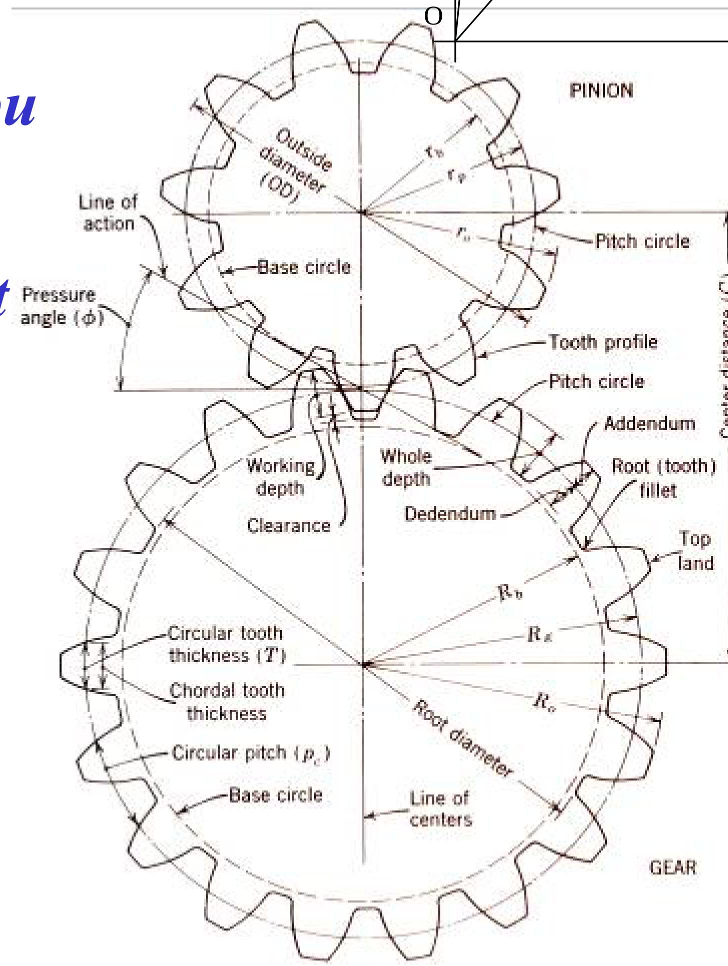
Gears are fun!

Design them well

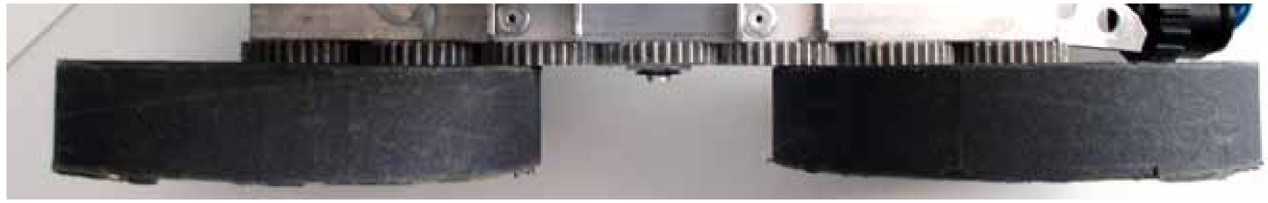
And when you are done

Your product will sell!



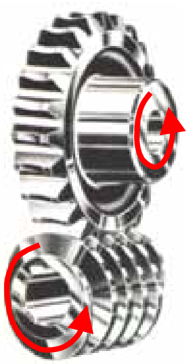


Gears: *Gear Trains*

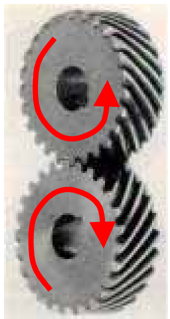


- A simple *gear train* to reduce motor speed and increase output torque:

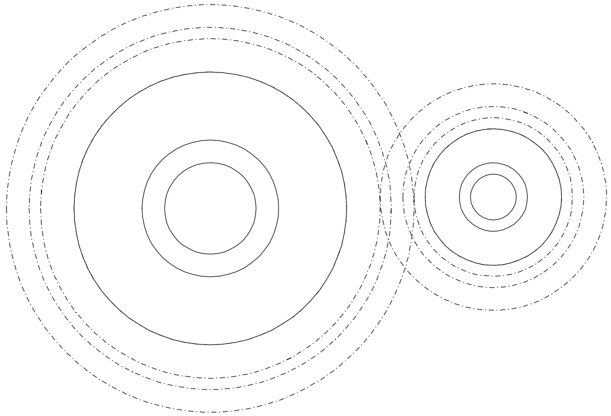
The nice solid models are by Prof. Martin Culpepper, see http://psdam.mit.edu/2.000/start.html

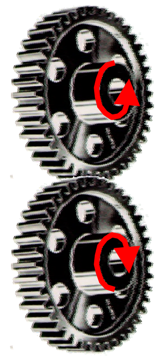


Worm Gears

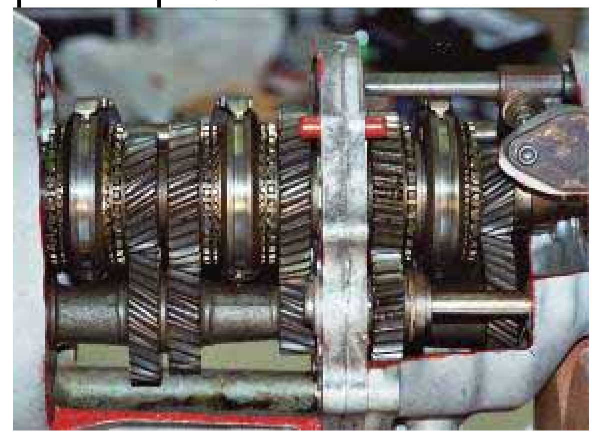


Helical Gears





Spur Gears



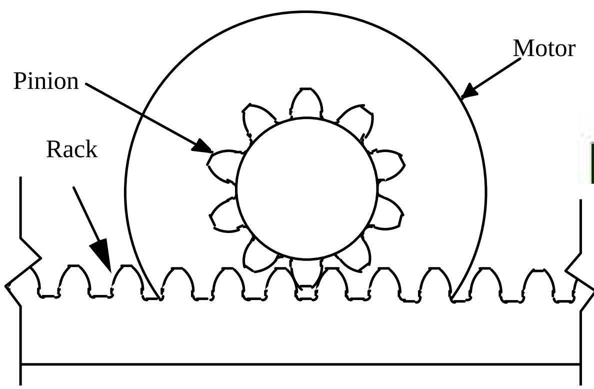
  - *Pinion:* smaller of two gears (typically on the motor) drives a gear on the output shaft
  - *Gear or Wheel:* Larger of the two gears

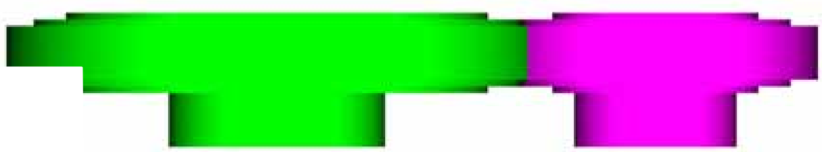
- Gears are highly efficient (90-95%) due to primarily rolling contact between the teeth; thus by conservation of energy:

$$\eta\Gamma_{\text{motor torque}} D_{\text{input gear diameter}} = \Gamma_{\text{output torque}} D_{\text{output gear diameter}}$$

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

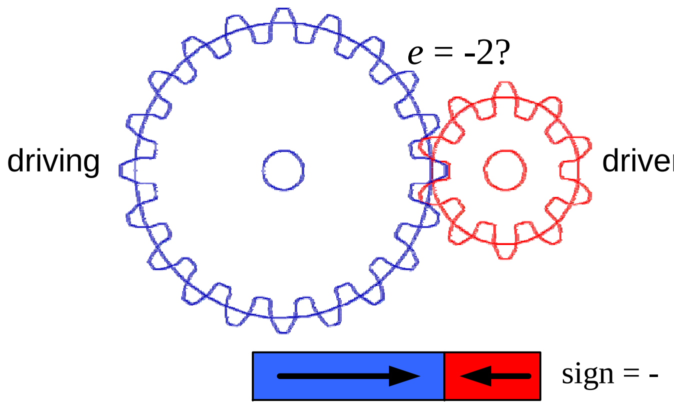
$$\Gamma_{output} = \frac{\eta\Gamma_{input} d_{output}}{d_{input}}$$

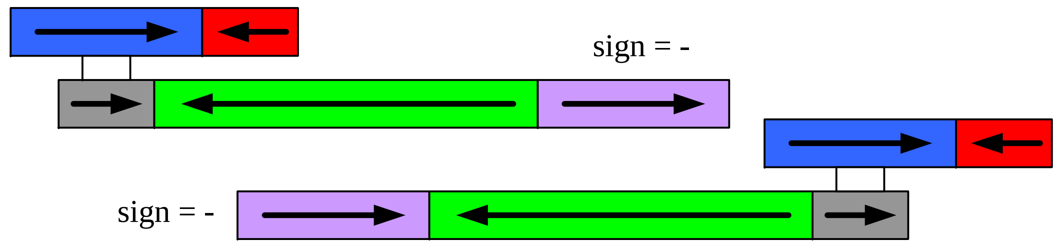


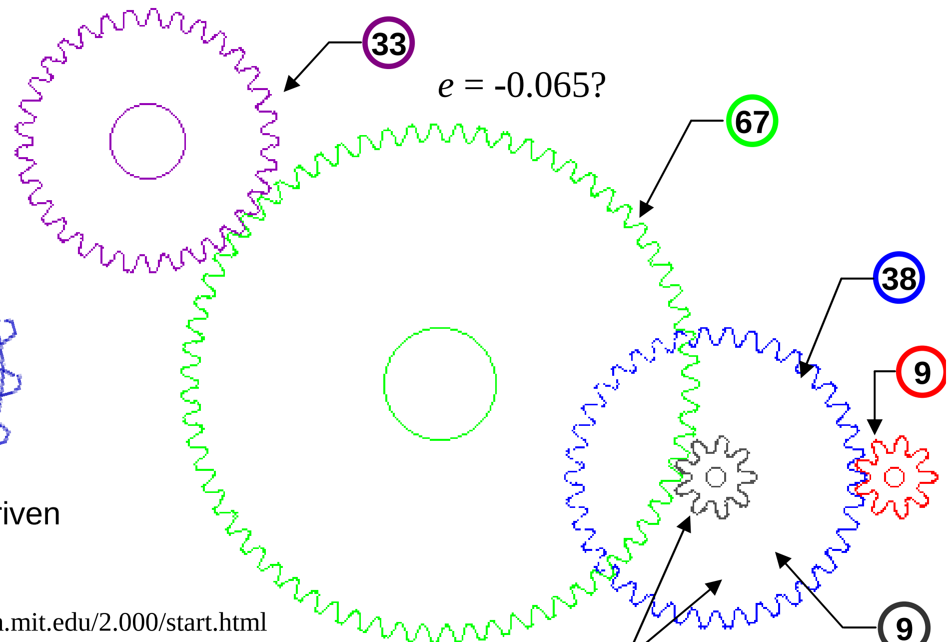


Gear Trains: *Serial Gear Train Ratios*

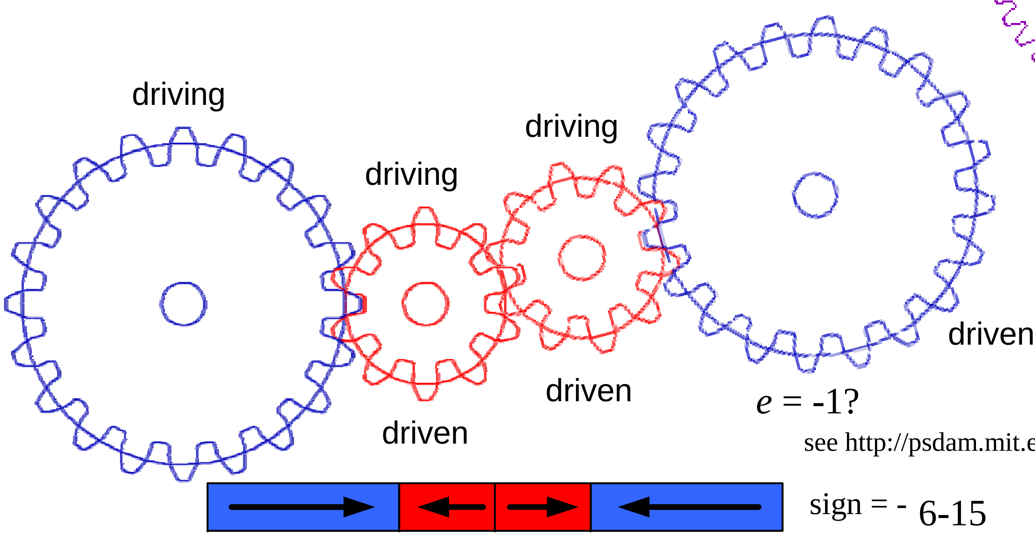
- For gears arranged in series (serial trains), identify the *driving* and *driven* gears and the relative direction of rotation (sign) between the input and output gears
  - Draw arrows on the gears: head-to-head or tail-to-tail, head to right is +
  - A negative transmission ratio means that the output rotation direction is opposite the input rotation direction







These two gears are rigidly attached to each other



see http://psdam.mit.edu/2.000/start.html

Ever wonder what's inside an electric screwdriver?

Gears: *Planetary Gear Trains*

- Planetary (epicyclic) gear trains enable a high reduction ratio to be obtained in a small place
  - With a fixed ring gear, as the planet carrier rotates, the planet gears must simultaneously roll on both the surfaces of the sun gear and the ring gear (review page 6-8)
  - The *difference* in the path length must be accommodated by rotation of the sun gear:

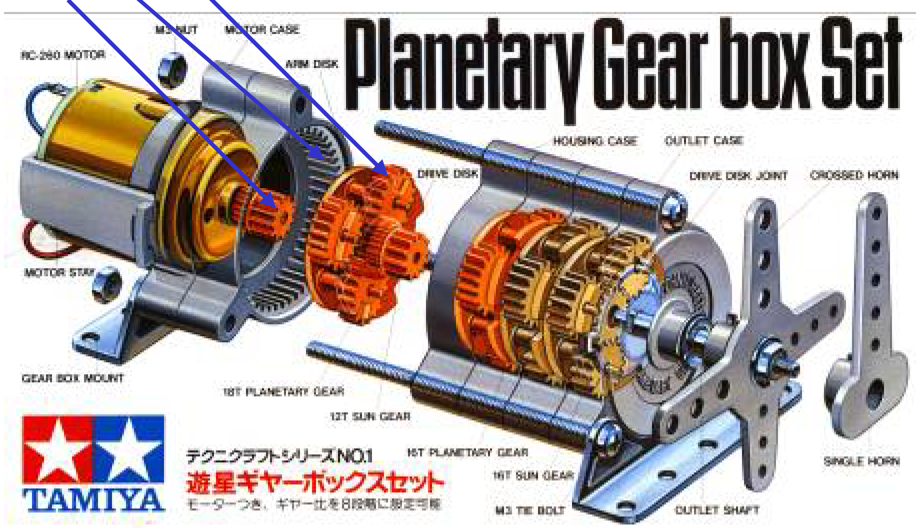
For each stage of the common planetary system shown below: $$\mathrm{TR}_{Transmission\ ratio} = \frac{D_{Sun} + D_{Ring}}{D_{Sun}}$$

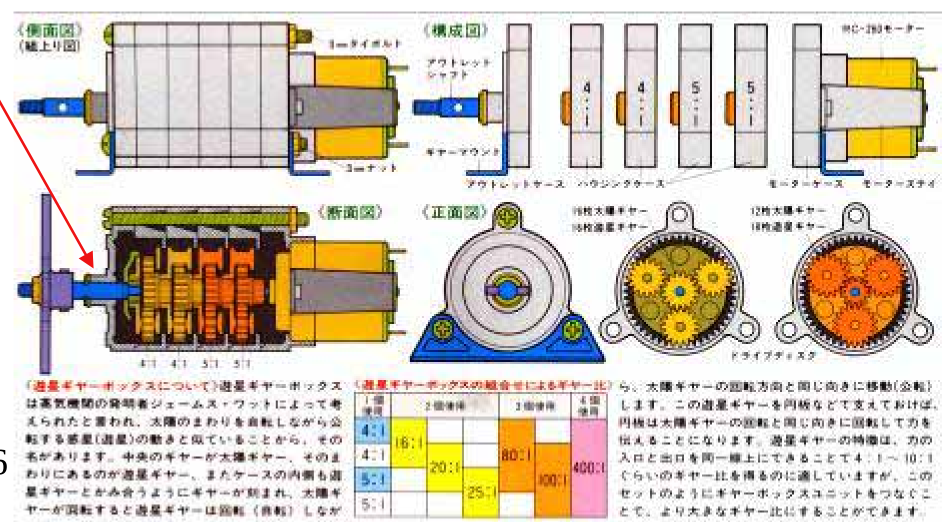
- The size of the teeth and the torque transmitted limit the minimum size of the sun gear
  - A sun gear can be mounted to a planet carrier's stem…..and a multistage system can be created
  - Very high ratios can thus be achieved but beware of high applied torques that can strip teeth!
  - Think of Saint Venant (page 3-5): Can the shaft support bending loads, or only transmit torque?

Planet

Ring

Sun



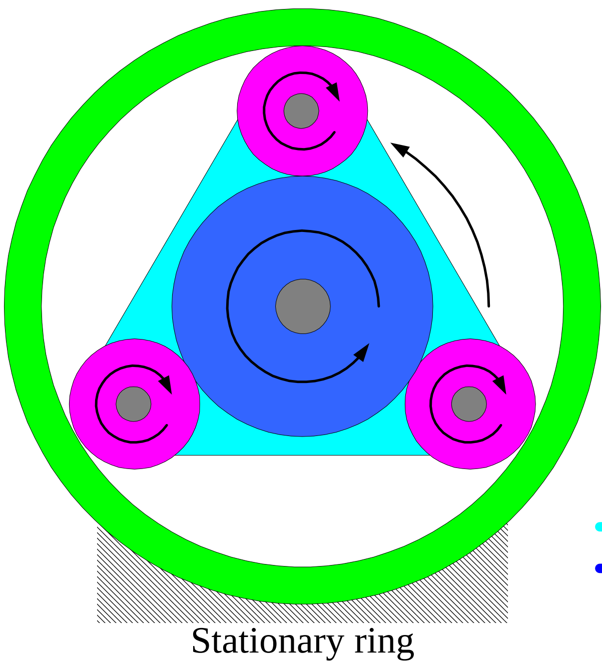


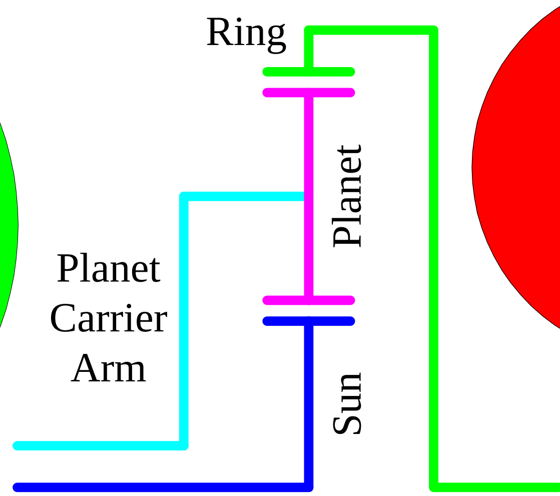
Epicyclic Drives: *Gear Train Ratios*

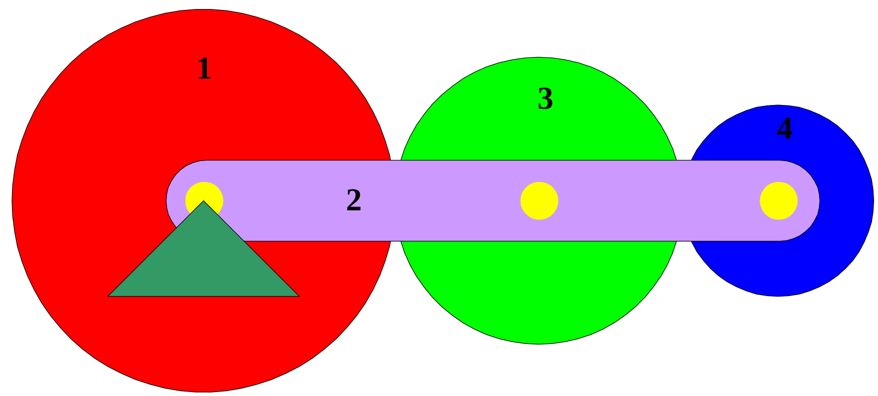
- The transmission ratio for an epicyclic gear train can be determined by considering the relative velocities of the components
  - There are 12 unique planetary gear transmissions

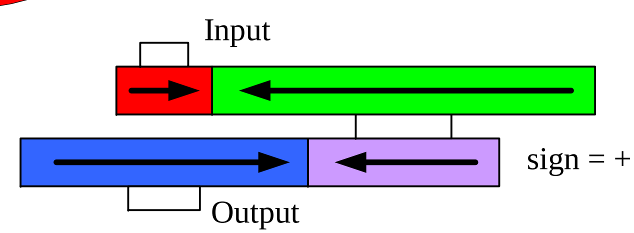
planetary.xls				
Enter numbers in BOLD, output in RED				
Written by Alex Slocum, last updated 3/05/03				
Gears	Generic	Type A (sun, planets on carrier, ring)		
Number of teeth on 1st driving gear	**20**	**30**	**72**	**30**
Number of teeth on 2nd driving gear (or enter 1)	**16**	**1**	**1**	**1**
Number of teeth on 1st driven gear	**30**	**72**	**30**	**72**
Number of teeth on 2nd driven gear (or enter 1)	**34**	**1**	**1**	**1**
relative direction of rotation (first to last gear)	**1**	**-1**	**-1**	**-1**
Train ratio	**0.31**	**-0.42**	**-2.40**	**-0.42**
Speed of first gear	**250**	**100**	**141.7**	**100**
Speed of last gear	**0**	**0**	**0**	**-41.7**
Speed of planet carrier arm	**-114.3**	**29.4**	**100**	**0**
Transmission ratio	**-2.19**	**3.40**	**0.71**	**-2.40**
Input		Sun	Planet carrier	Sun
Output		Planet carrier	Ring	Ring
Stationary		Ring	Sun	Planet carrier

To SEE how a planetary works, see http://psdam.mit.edu/2.000/vta/



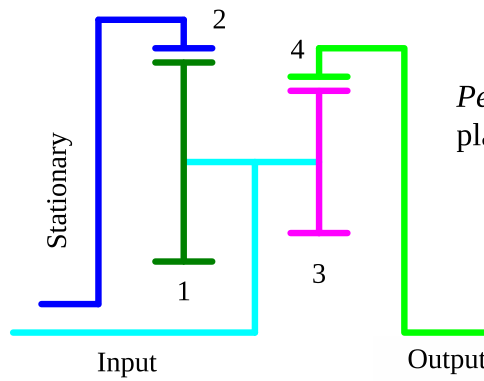






Gears: *More Epicyclic Drives*

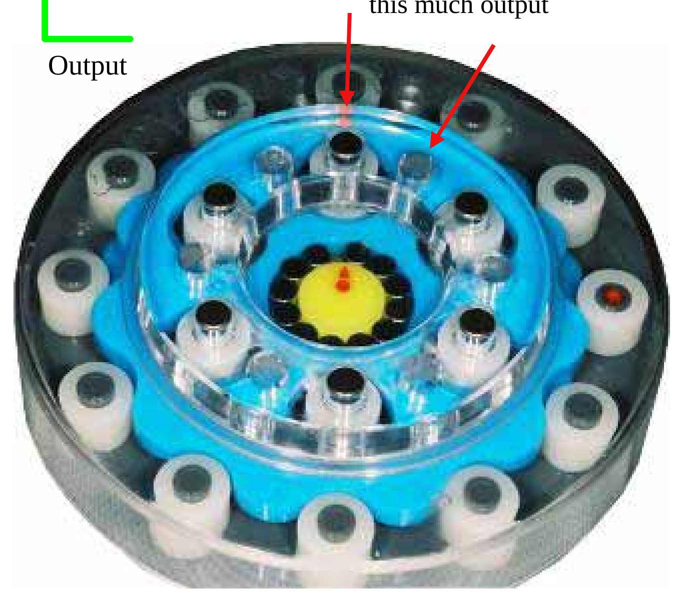
- The concept of differential motion can also be exploited using a wave generator to convert rotary motion from a motor into rotary motion of wave generator
  - The wave generator is forced to roll on two different surfaces at once which thus causes it to revolve and drive an output shaft
- Several different types of commercial systems are available, and are often used in industrial robots and indexing systems
  - Harmonic drives
  - Cycloidal drives



Perpetual wedge planetary schematic

www.hdsi.net

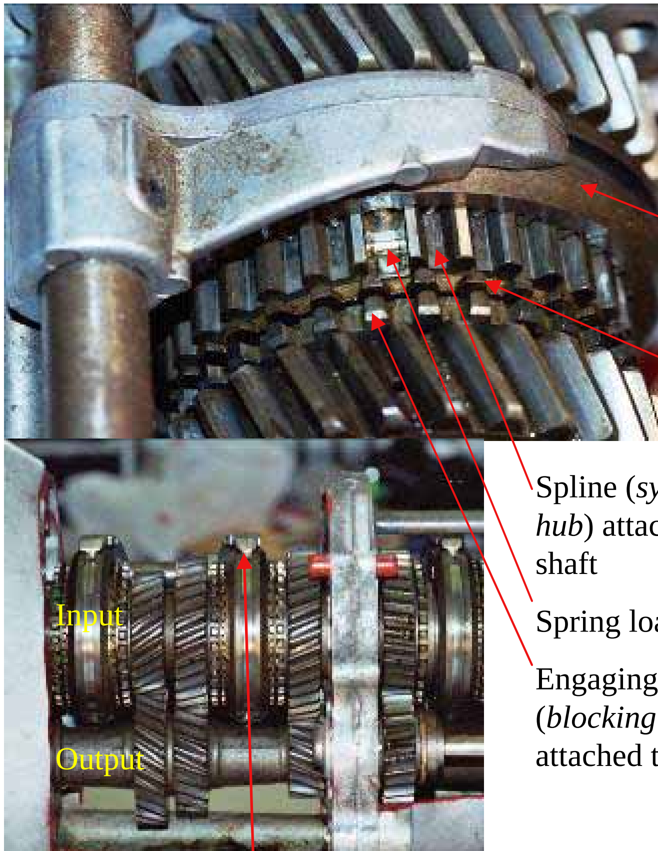
1 input revolution causes this much output



http://cyclo.shi.co.jp/eng/product/gmoter/saikuro6000/

Gears: *Automotive Transmissions*

- An automotive transmission is a truly amazing system
  - The shifter controls linkages that slide internal-toothed collars (*synchronizer sleeve*) over splined shafts connected to different gears and the input shaft to engage corresponding gears on the output coupling shaft
    - The synchronizer brings the drive gear up to speed before allowing the spline to engage it (no grrr-inding!)



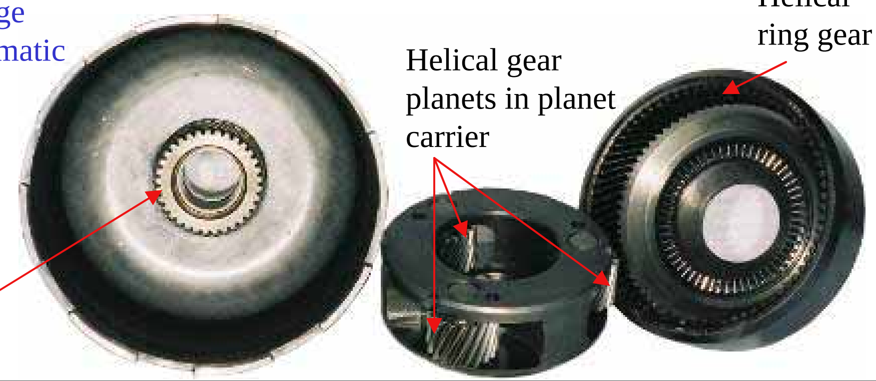
Spline (*synchronizer hub*) attached to input shaft

Spring loaded “dog”

Engaging spline (*blocking ring*) attached to gear

From the other side, note the shifter forks

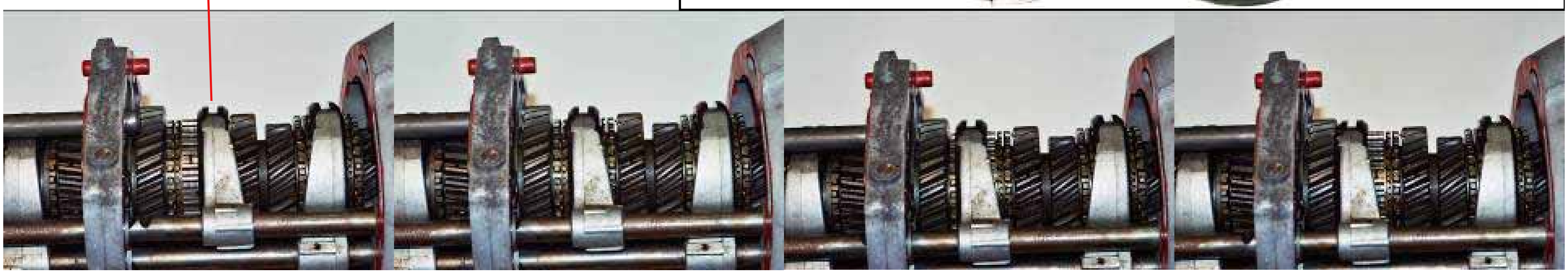
Planetary stage from an automatic transmission



Helical ring gear

Helical gear planets in planet carrier

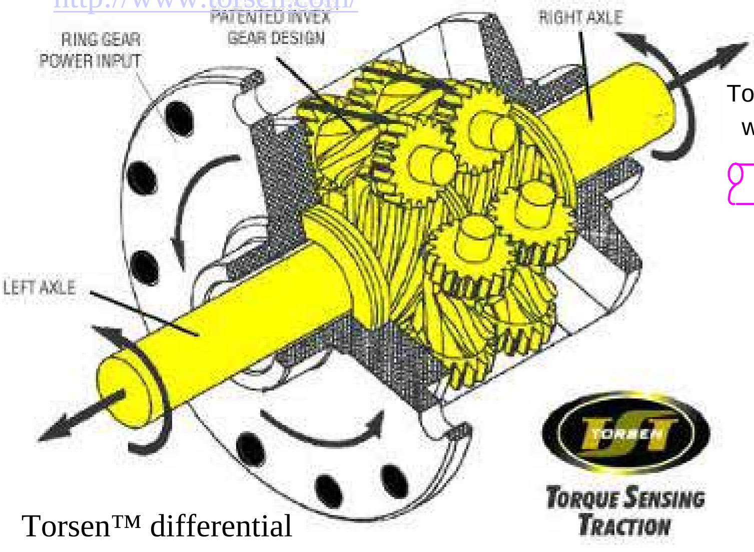
Helical sun gear



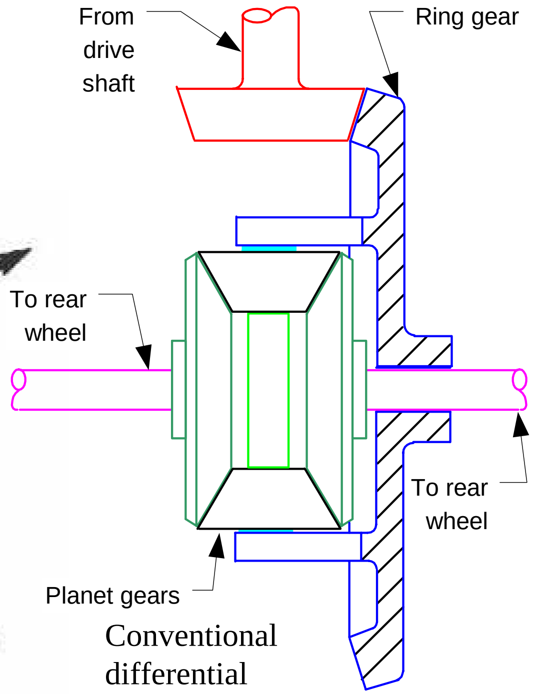
Gears: *Differentials*

- A differential allows for differential motion between output shafts
  - See page 5-17
- The Torsen™ differential was invented in by Vern Gleasman (US Patent 2,896,541), and uses helical gears and the principle of self-help
  - Helical gears’ thrust loads apply forces to friction clutches torque is delivered to the wheel that can use the torque, so wheels never spin as they can with a conventional open differential

http://www.torsen.com/

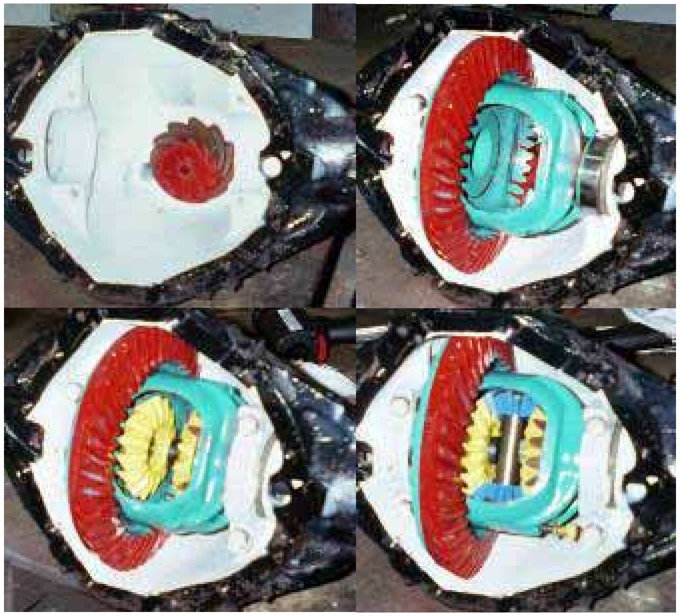


Torsen™ differential
(US Patent 4,491,035)



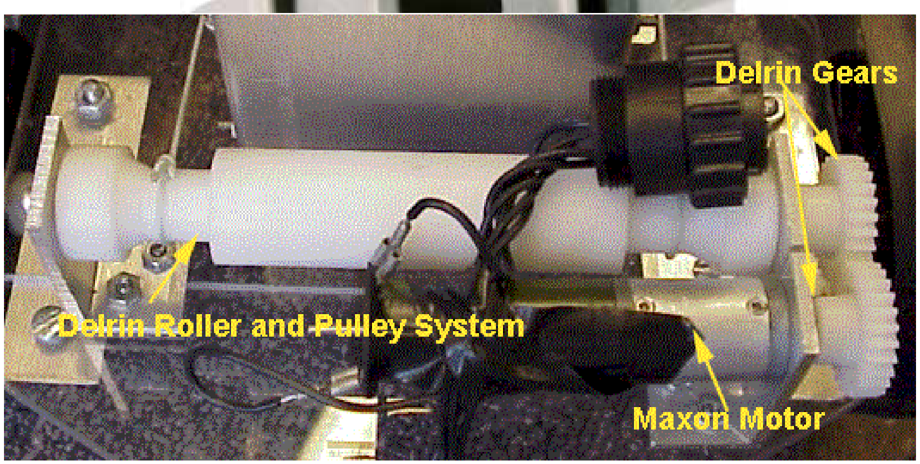
Conventional
differential

Assembly of a classic open differential (Thanks Bill Miskoe!)

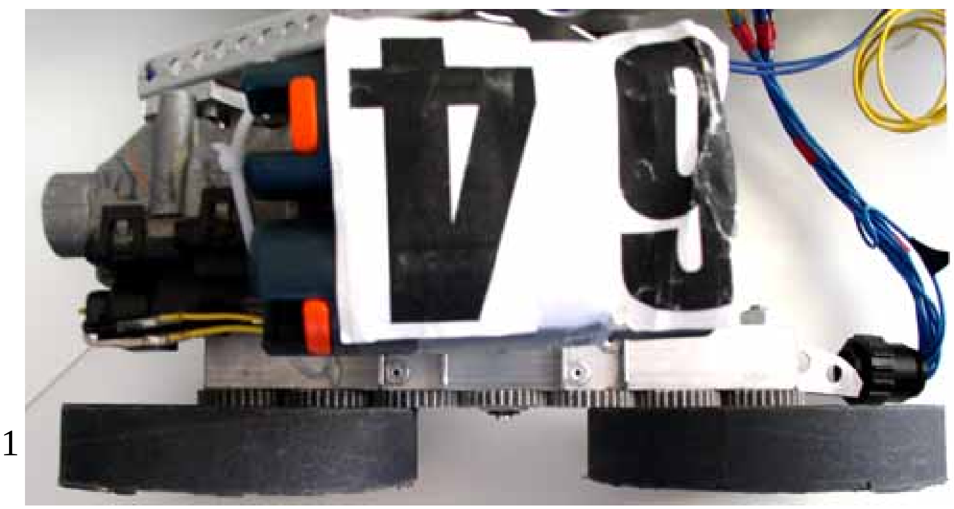


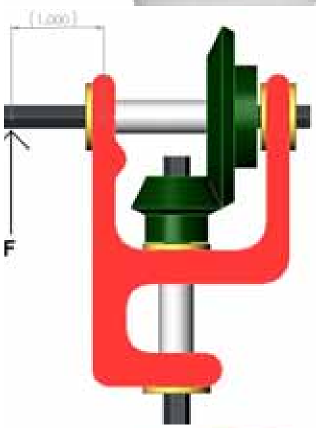
Gears: *Robot Design Contest Kits*

- There are usually a large number of gears available for a design contest
- Spur gears are the most commonly used gears, & they have straight *involute* teeth
  - Justify your designs with basic engineering calculations
    - Show the system will achieve the desired speed and torque requirements
    - Determine the stresses in the gear teeth
    - Students who strip gear teeth should not be given replacement gears until they fix their calculations and adjust the design accordingly!
  - In addition to spur gears, bevel gears may also be available

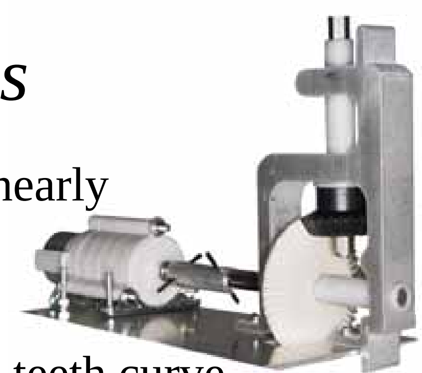


Martin Jonikas' machine, winner of 2002 *The MIT and the Pendulum*

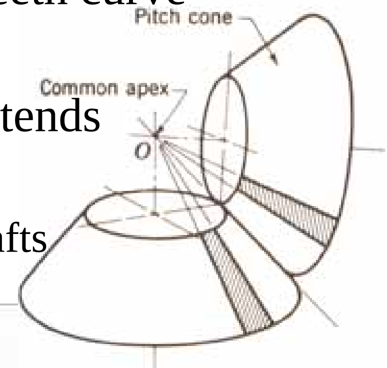


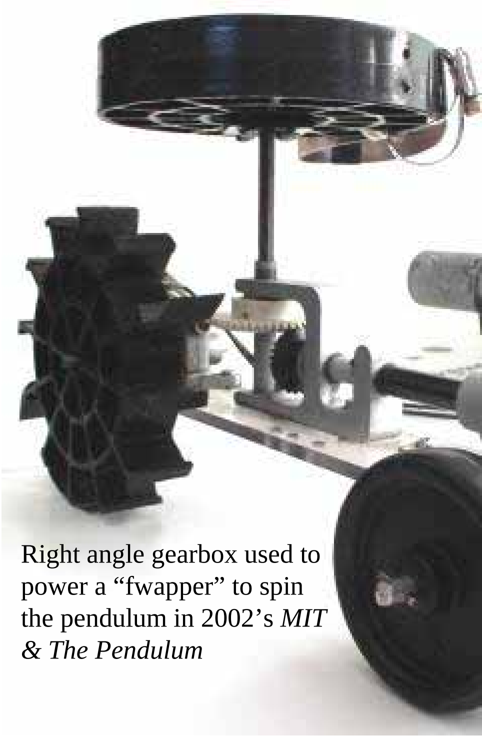


Gears: *Spur and Straight Bevel Gears*

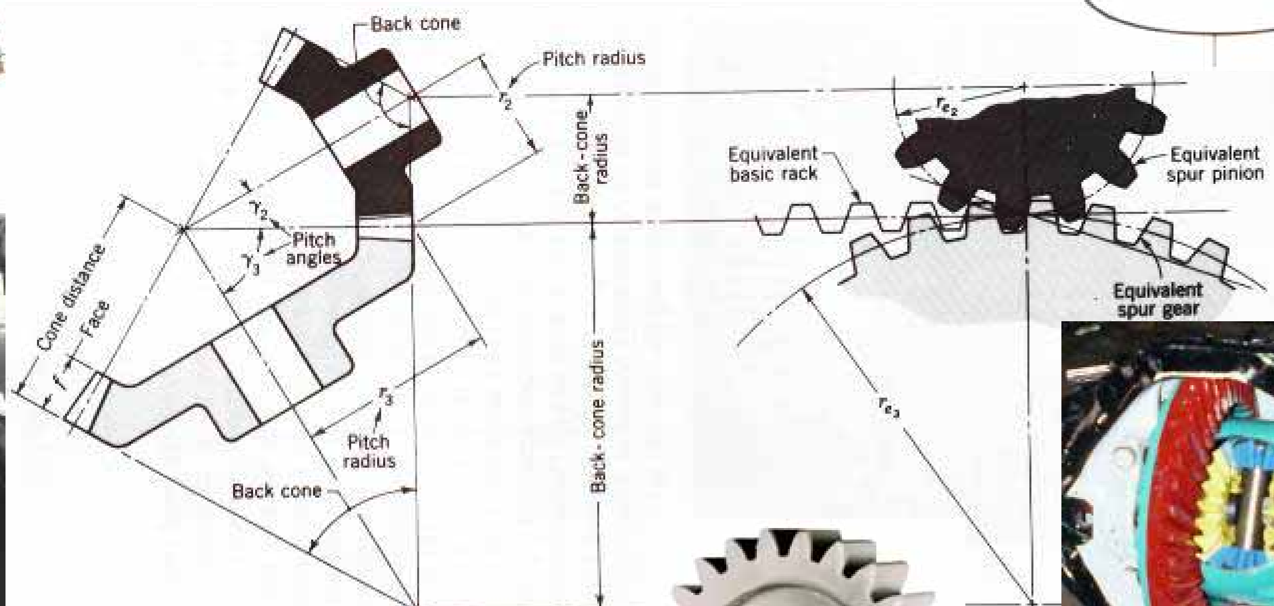


- Spur gears have an involute cross section that extends linearly along the gear's axial direction
  - They are the most common type of gear
- Helical gears also have an involute cross section, but the teeth curve around on a helical trajectory
- Straight bevel gears have an involute cross section that extends linearly on the surface of a cone towards the apex
  - They can be used to transmit torque between intersecting shafts



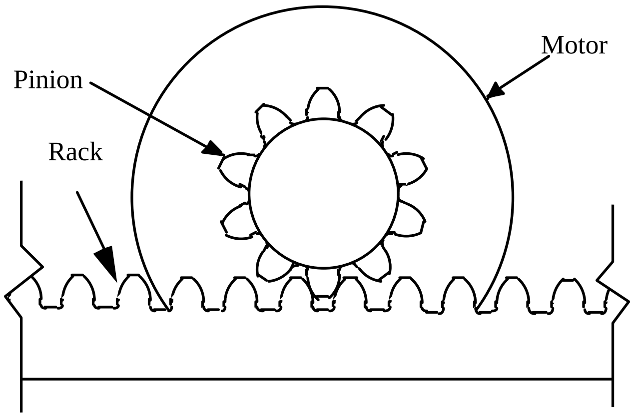


Right angle gearbox used to power a "fwapper" to spin the pendulum in 2002's *MIT & The Pendulum*



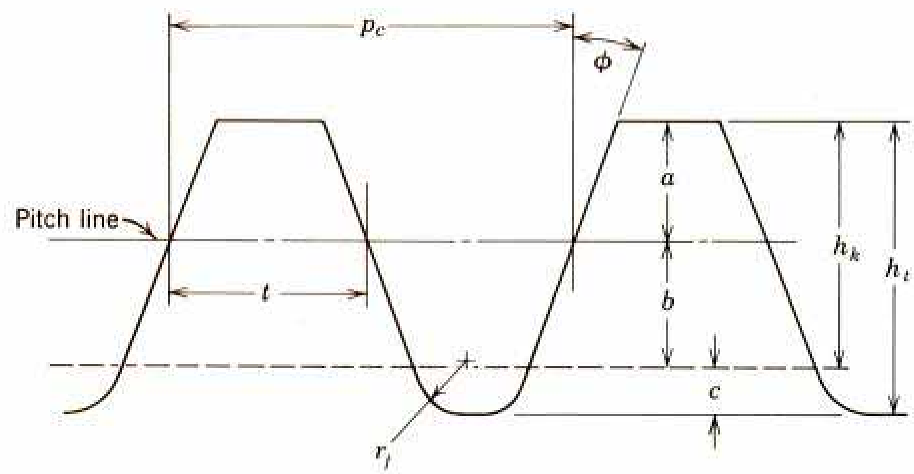
Gears: *Rack & Pinion*

- A rack and pinion is one of the least expensive methods of converting rotary motion to linear motion (what about reciprocity!)



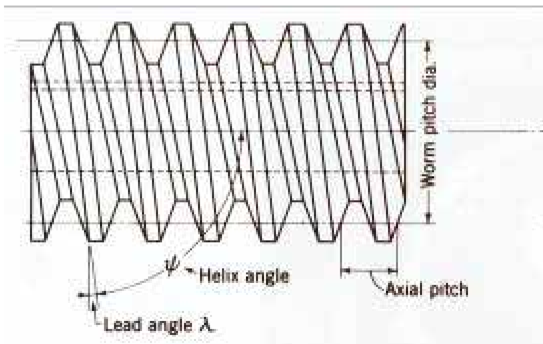
  – It does not provide a mechanical advantage like a leadscrew

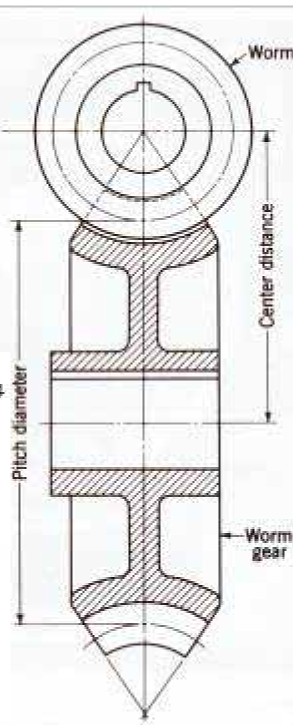
- Tooth forces acting on the pressure angle push the pinion away from the rack

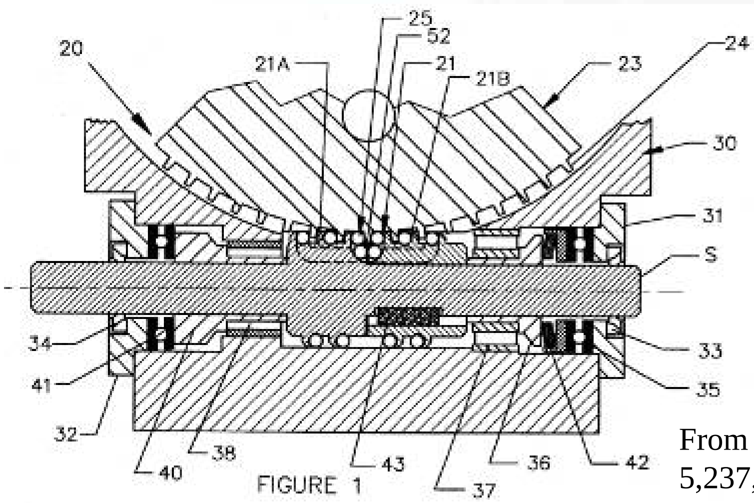


Gears: *Worm*

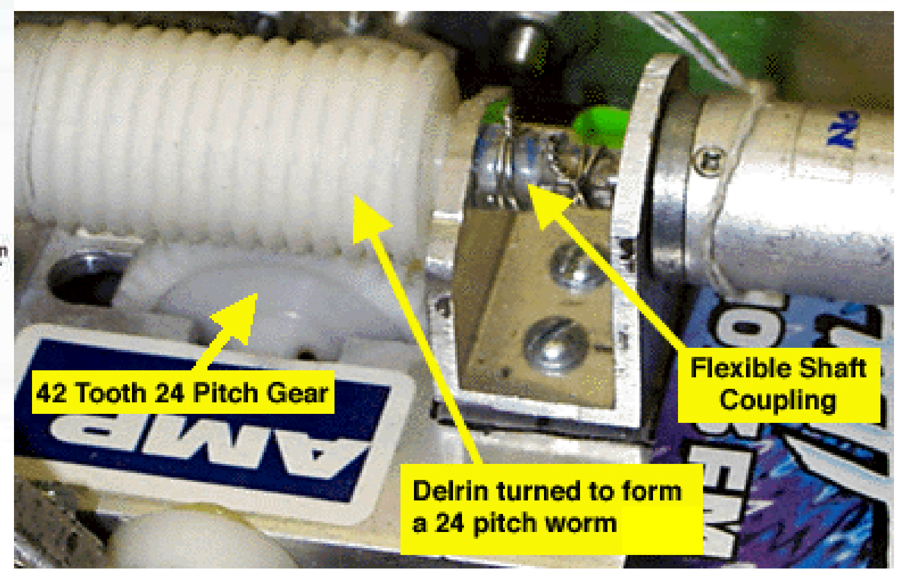
- The transmission ratio is a function of the worm pitch and the worm gear pitch diameter
  - As the worm rotates, its thread pushes the teeth on the worm gear (wheel, or driven gear)
  - Given the lead ℓ_{worm} of the worm and the diameter D of the driven gear, the transmission ratio of a single worm gear set is just $TR = \pi D_{pitch} / \ell_{worm}$
- The contact between the teeth is sliding, so the efficiency may only be 30-50%
  - You can create a worm using a leadscrew and it can contact the teeth of a spur gear… *(this is called blacksmithing!)*







From US Patent 5,237,886



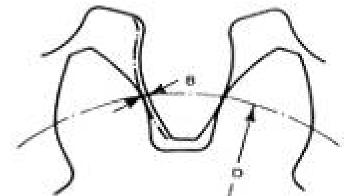
Gears: *Selection of Parameters*

- Spreadsheet *spurgears.xls* for conservative estimations of spur gear tooth stress
- Note that the pinion stress is at its limit
  - You will have to think of ways to prevent a single gear's teeth from being stripped!
- For long life in real products, service factors and many other critical geometry checks need to be performed
  - Consult the *Machinery's Handbook*, or a gear design handbook or AGMA standards
  - Proper tooth design involves more careful assessment of the tooth geometry and loads using the *Lewis Form Factor*
  - Improper lubrication is often the greatest cause of gear failure

	Safe bending stress (psi)	
Plastic	**Unfiled**	**Glass-filled**
ABS	3000	6000
Acetal	5000	7000
Nylon	6000	12000
Polycarbonate	6000	9000
Polyester	3500	8000
Polyurethane	2500	

SpurGears.xls		
Spreadsheet to *estimate* gear tooth strength		
Production gears must be designed using the Lewis Form Factor or FEA		
Written 1/18/01 by Alex Slocum		
Inputs		
Torque, T (in-lb, n-m)	8.8	1.0
Pressure angle, f (deg, rad)	20	0.34907
Pitch, P	24	
Number of teeth on pinion, Np	12	
Number of teeth on gear, Ng	48	
Center distance tolerance, Ctol (inches)	0.005	
Face width, w (inches)	0.188	
Pinion yeild stress, sigp (psi)	6000	
Gear yield stress, sigg (psi)	6000	
Stress concentration factor at tooth root, scf	1	
Outputs		
Gear ratio, mg	4	
Pinion pitch diameter, Dp (inches)	0.500	
Gear pich diameter, Dg (inches)	2.000	
Center distance, C (inches)	1.255	
Tooth thickness, tt (inches)	0.0654	
Addendum, a (inches)	0.0417	
Dedendum, b (inches)	0.0520	
Clearance, cl (inches)	0.0103	
Pinion tooth force, Fp (lbs)	8.85	
Gear tooth force, Fg (lbs)	2.21	
Tooth section parameters		
Chordal area, Ac (inches^2)	0.0123	
First Moment, Q (inches^3)	2.01E-04	
Moment of Inertia, I (inches^4)	4.39E-06	
Distance Nuetral axis to outer fiber, cc (inches)	0.0327	
Pinion tooth stresses (stress ratio must be less than 1)		**stress ratio**
Shear stress of the tooth (F/A) (psi)	719	0.21
Bending shear stress (FQ/wI) (psi)	2157	0.62
Bending stress (F(b+a)c/I) (psi)	6855	1.14

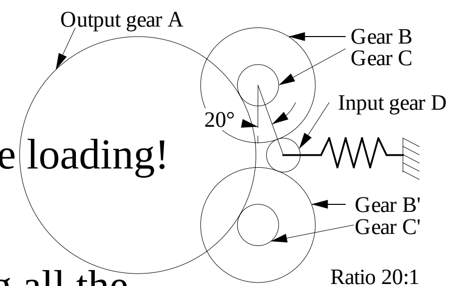
Gears: *Accuracy*, *Repeatability*, & *Resolution*



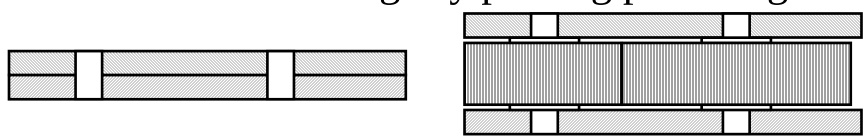
Backlash, it must be managed!

- The shafts and bearings that support them must be carefully spaced and aligned
  - Center distance is half the sum of the pitch diameters + a small amount (0.1 mm):

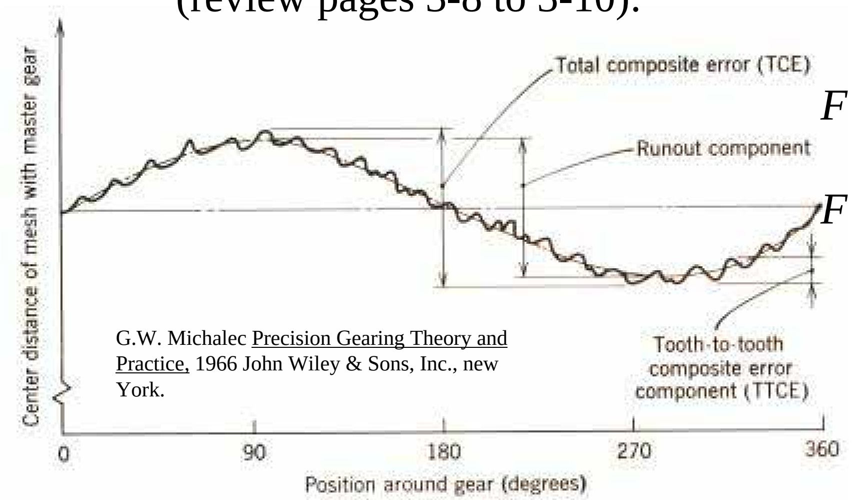
$$L_{distance\_between\_shafts} = \frac{\left(D_{output\ pitch\ diameter} + D_{input\ pitch\ diameter}\right)}{2} + \delta$$



  - No wobble!: The axes of rotation must be kept parallel to prevent tooth edge loading!
- Manufacturing is key!
  - Line-bore holes for shafts and bearings by pinning plates together & drilling all the holes at once!



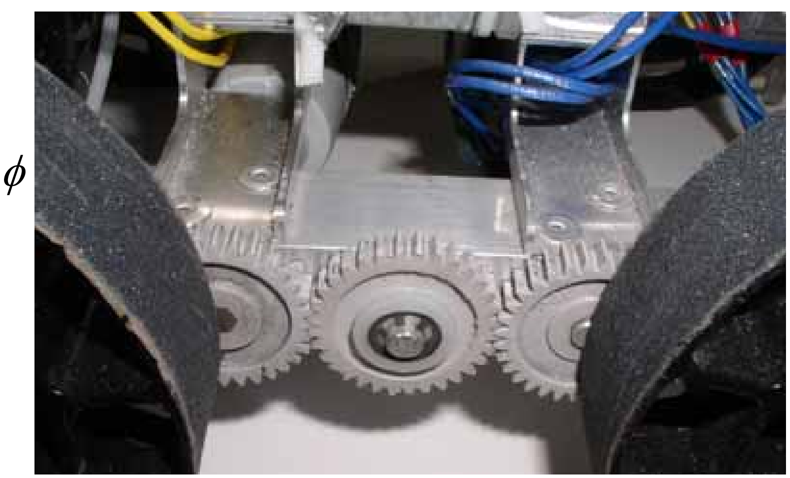
- The bearings and shaft must withstand the speed and loads generated
  - Angular deflection are amplified by distance and can lead to tooth skip and backlash (review pages 3-8 to 3-10):



G.W. Michalec Precision Gearing Theory and Practice, 1966 John Wiley & Sons, Inc., new York.

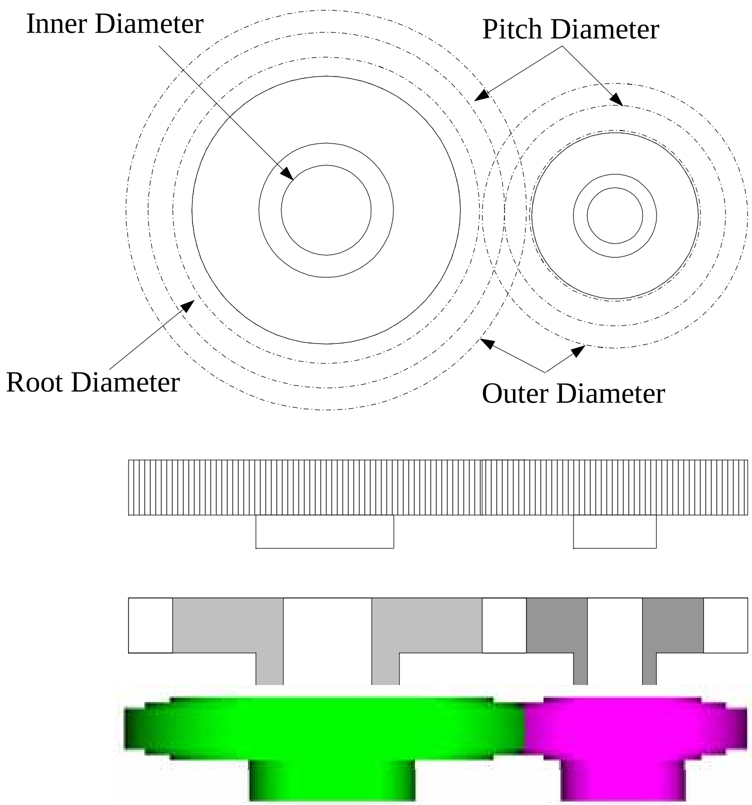
$$F_{radial} = \frac{2\Gamma}{D_{pitch}}$$

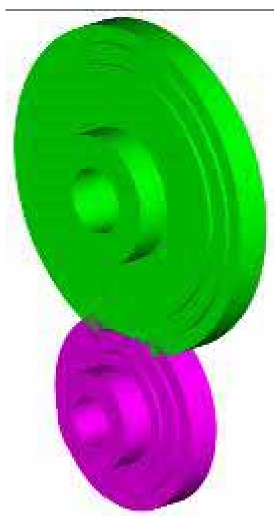
$$F_{spread} = F_{radial} \sin\phi$$

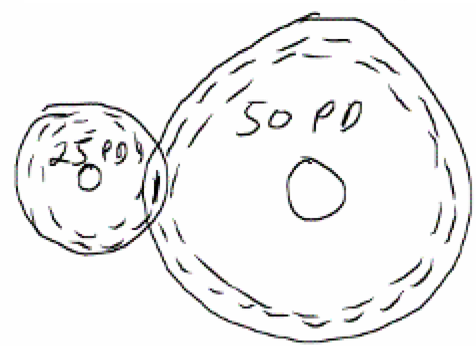


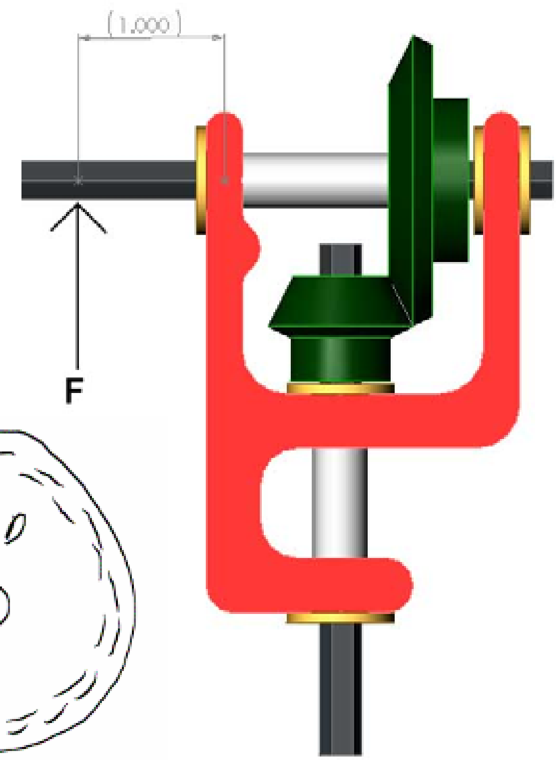
Gears: *CAD Modeling*

- There are two types of gear models:
  - A geometry placeholder in a drawing of a system shows the gear ratio by means of the gears' pitch diameters
    - It can be hand-sketched or shown with a CAD system, and it does not include tooth detail, nor does it need to
  - An accurate mathematical representation of the gear created by gear design software to allow for the examination of the contact region as the gears rotate
    - This is way beyond the needs of an introductory design course





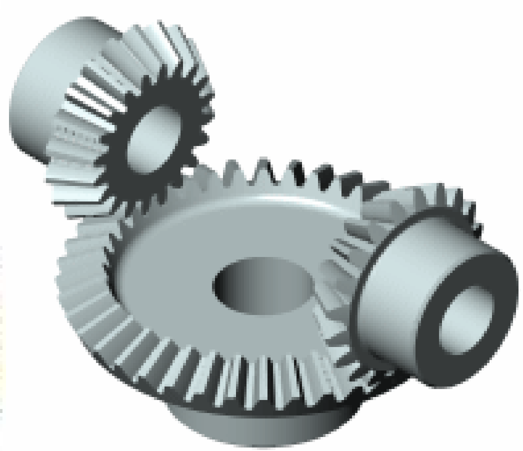




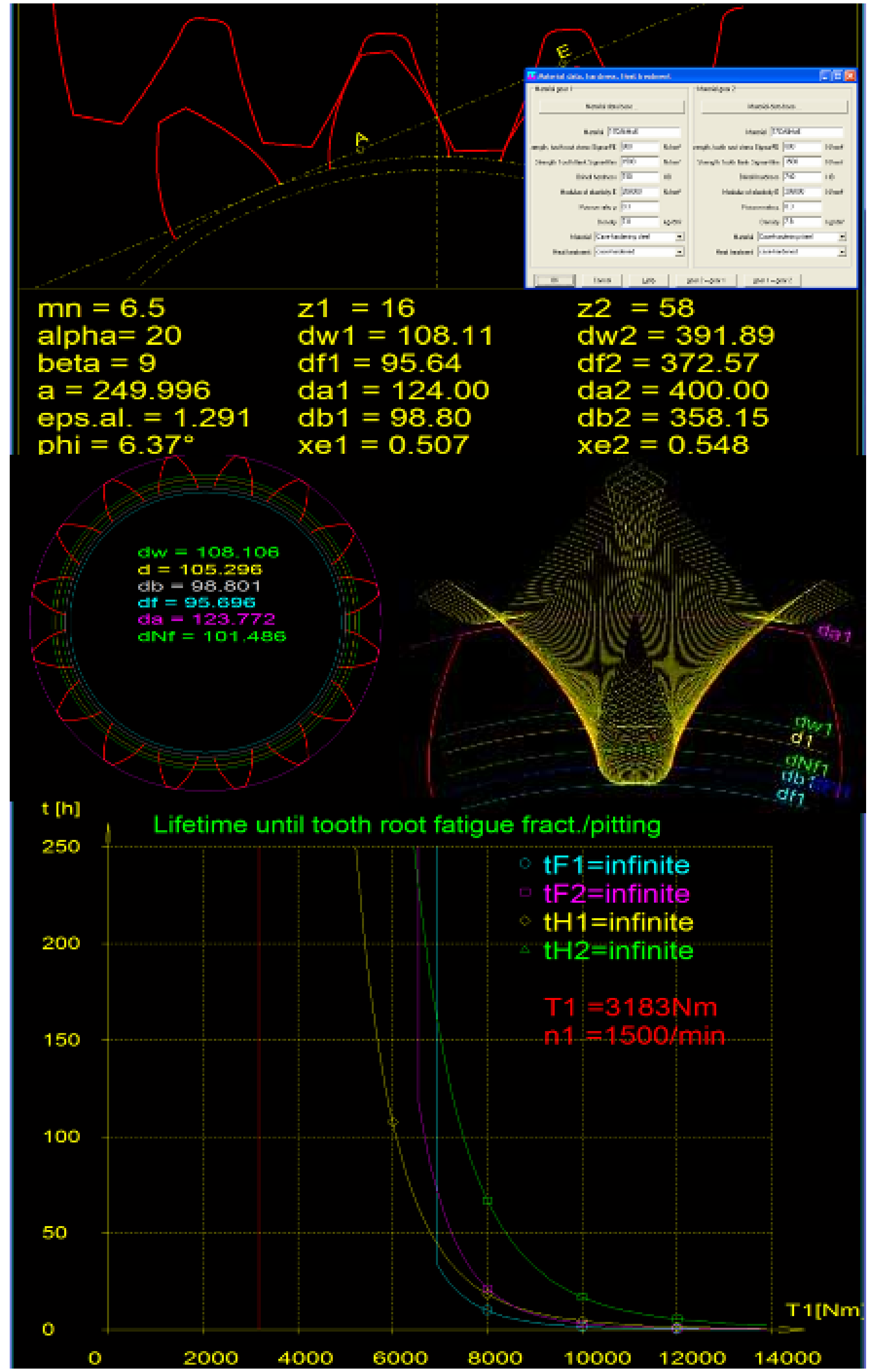
Gears: *Gear Design Software*

- Gear design software allows for the input of every possible parameter from primary geometry, to loading, to tolerances, to materials…
  - Output ranges from life and accuracy information as well as cutter design and manufacturing information
  - CAD outputs range from .dxf drawings to IGES files to part files in different solid model formats
- A must for engineers designing custom gears for production

http://www.camnetics.com/

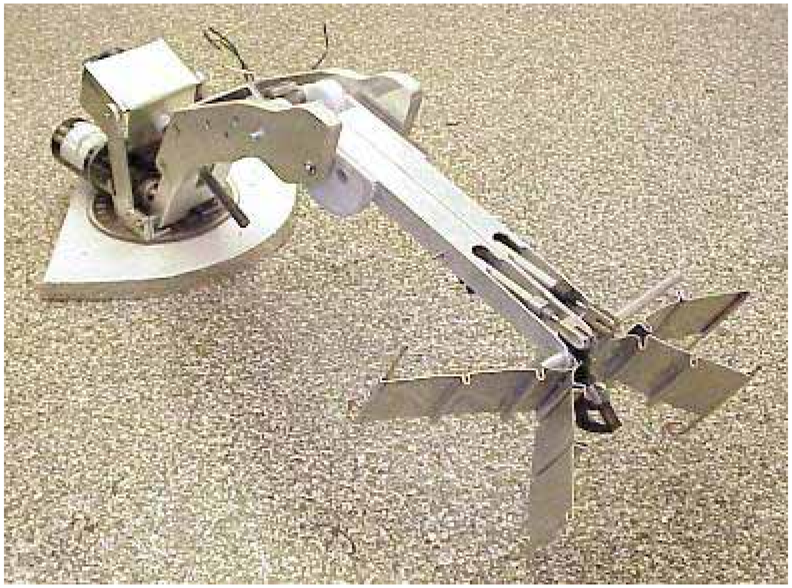


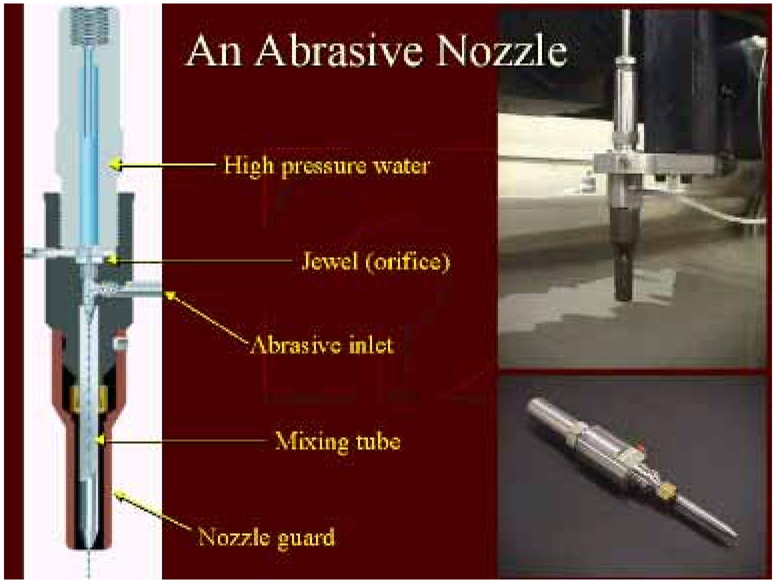
ZAR1 demo from HEXAGON Software, http://www.hexagon.de/zar1_e.htm



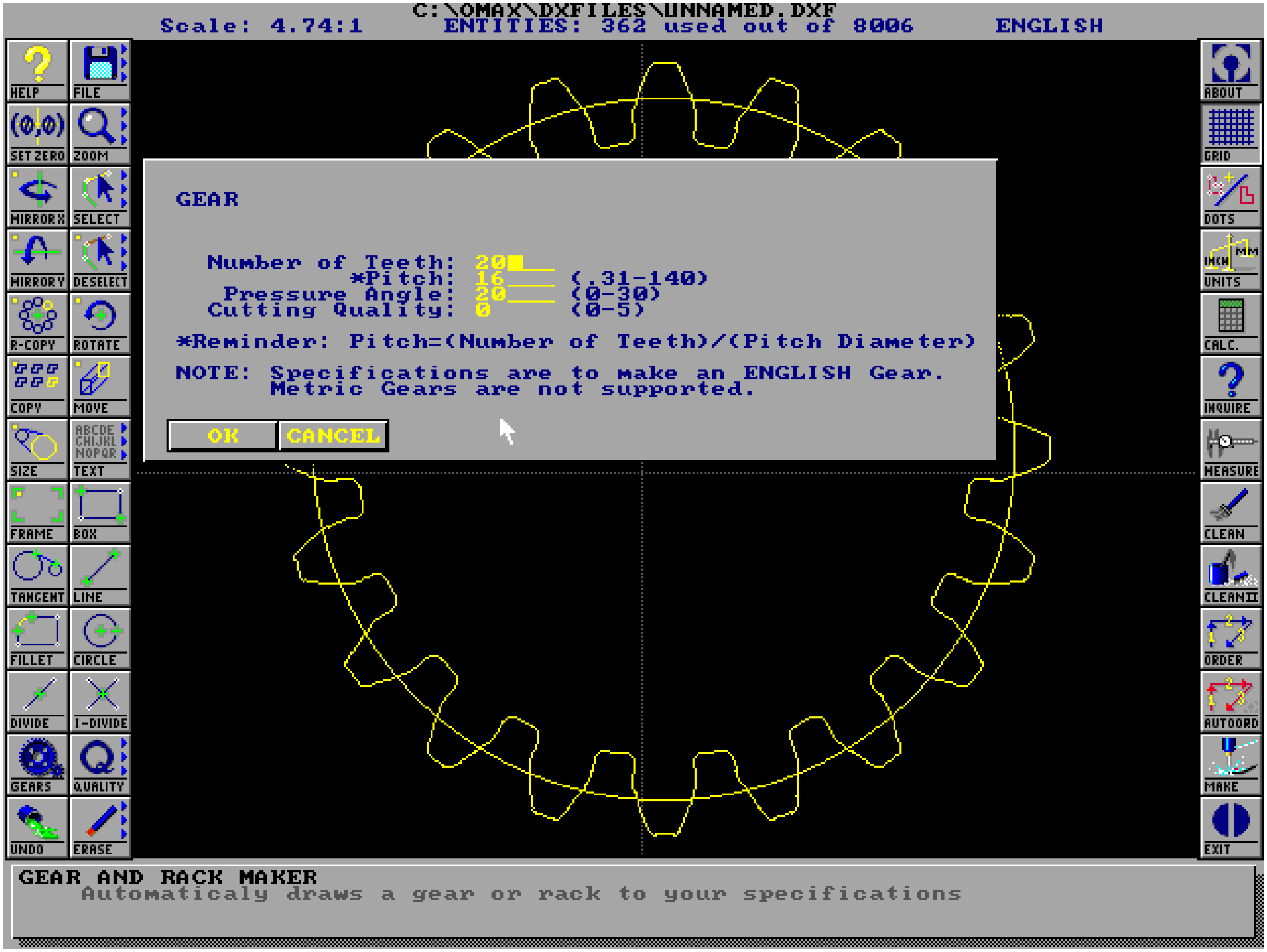
Gears: *Manufacturing by Abrasive Waterjet*

- It's easy to manufacture prototype gears for low speed low cycle use on the OMAX Abrasive Waterjet Machining Center™
  - All that is needed is to specify pitch, pressure angle, and pitch diameter
    - You must have previously calculated the proper design parameters to make sure the gears do not fail in bending or shear
  - Your solid model in your assembly should show the gears without teeth, just model them using the pitch diameter
  - Ayr Muir-Harmony designed and built his own large diameter needle bearings, leadscrew, and planetary gear system for the turntable
    - Check out his web site: http://web.mit.edu/afs/athena.mit.edu/user/a/y/ayr/www/finalrep/

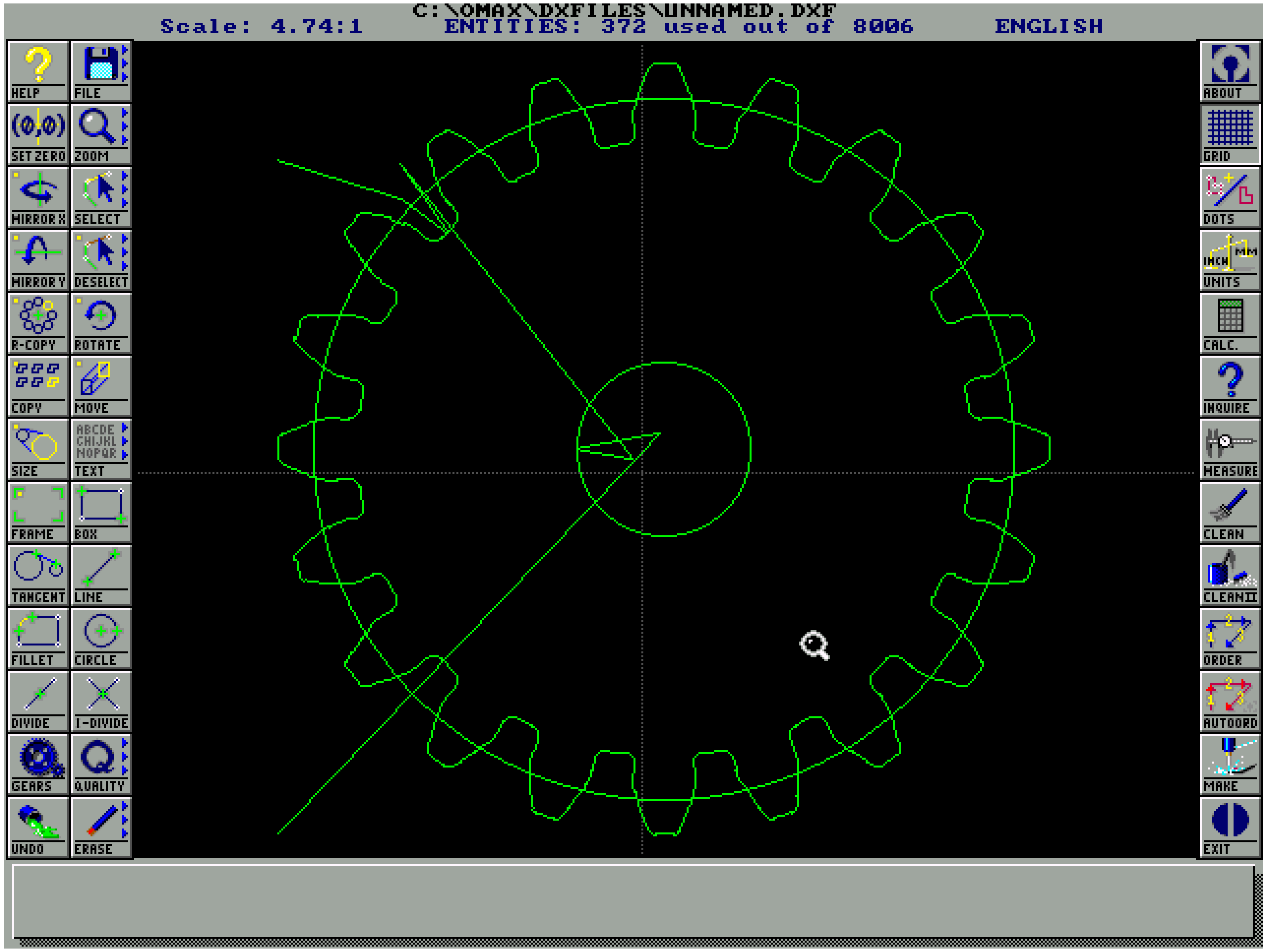




Gears: *Step 1 Define the Parameters*

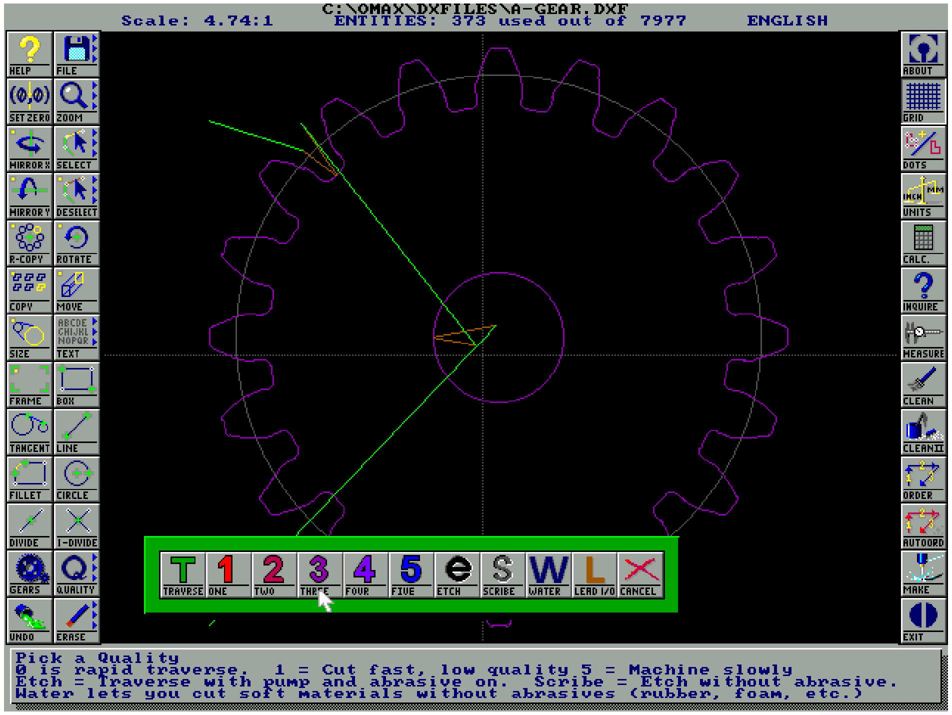


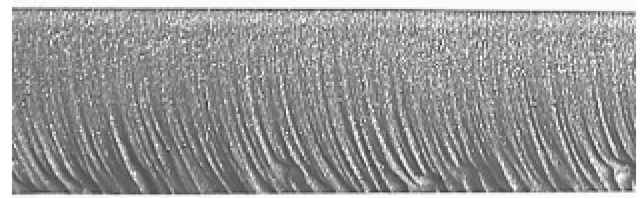
Gears: *Step 2 Add Center pilot hole and Lead-In/out lines*

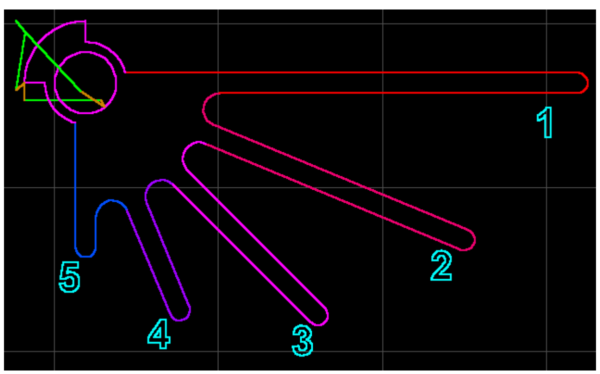


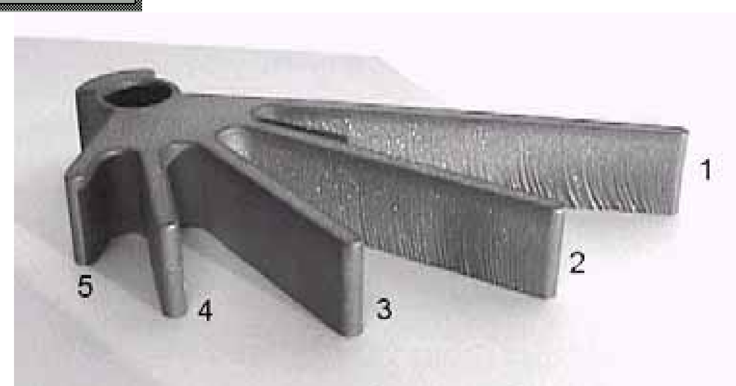
Note: The waterjet can be used to create a pilot hole for the center which is then made very accurate by drilling. Do you need a keyway?

Gears: *Step 3 Define Path Quality*

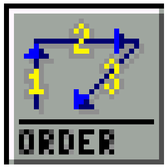


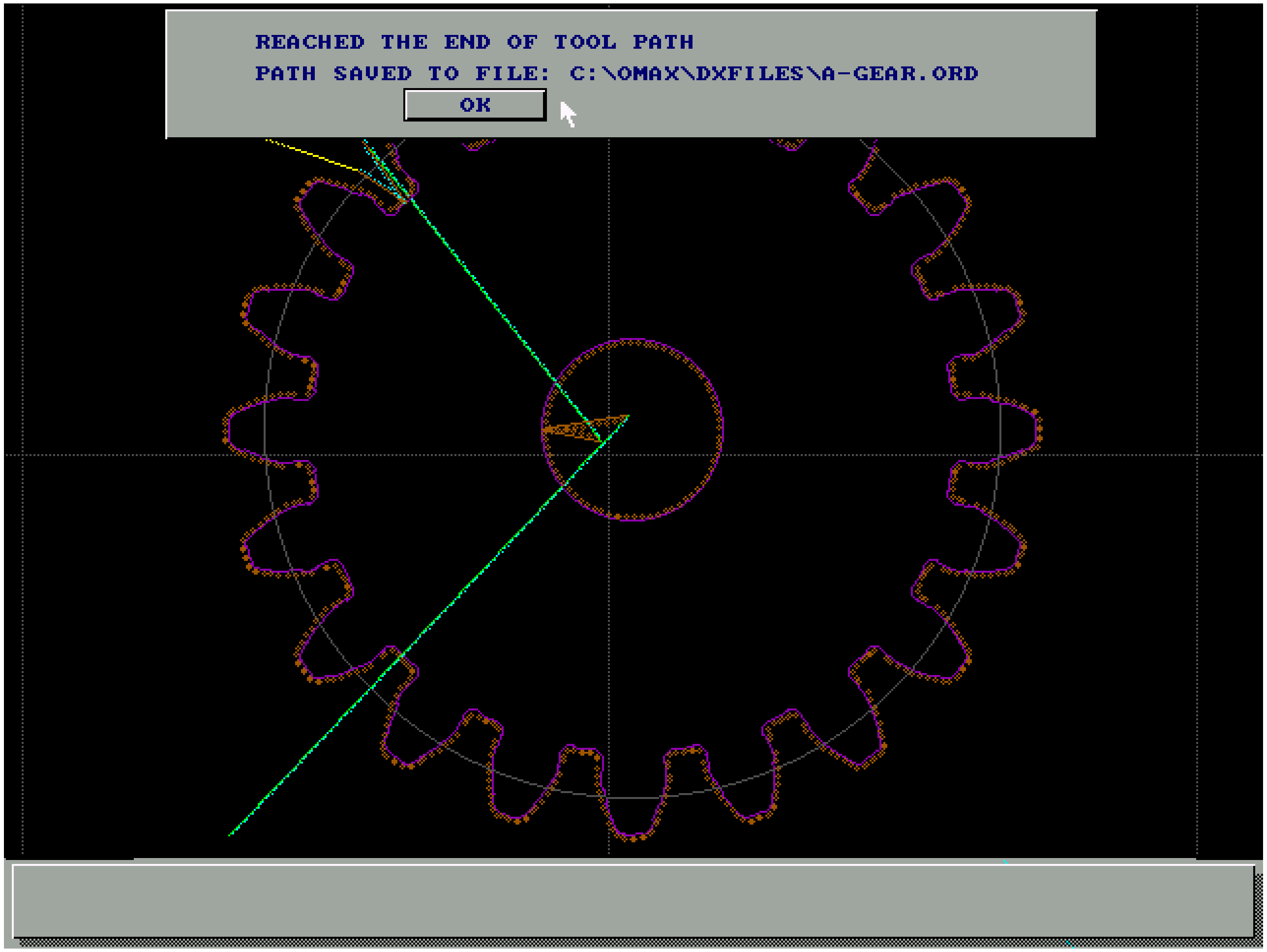


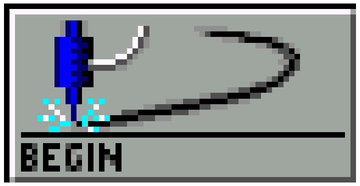




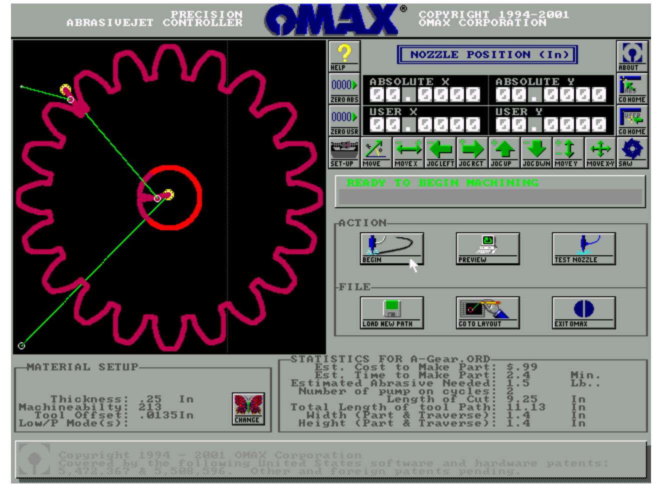
Gears: *Step 4 “Order” the tool path (make a .ord file)*



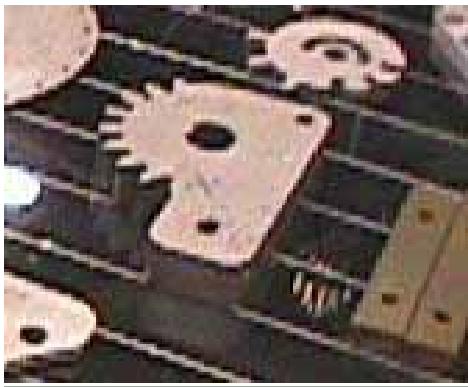


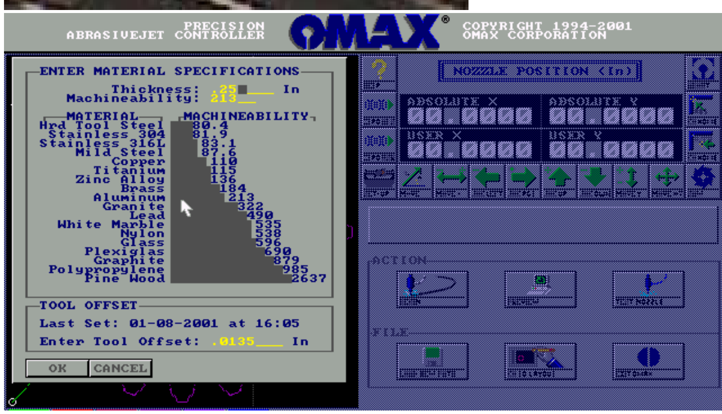


Gears: *Step 5 Make & Voila!*

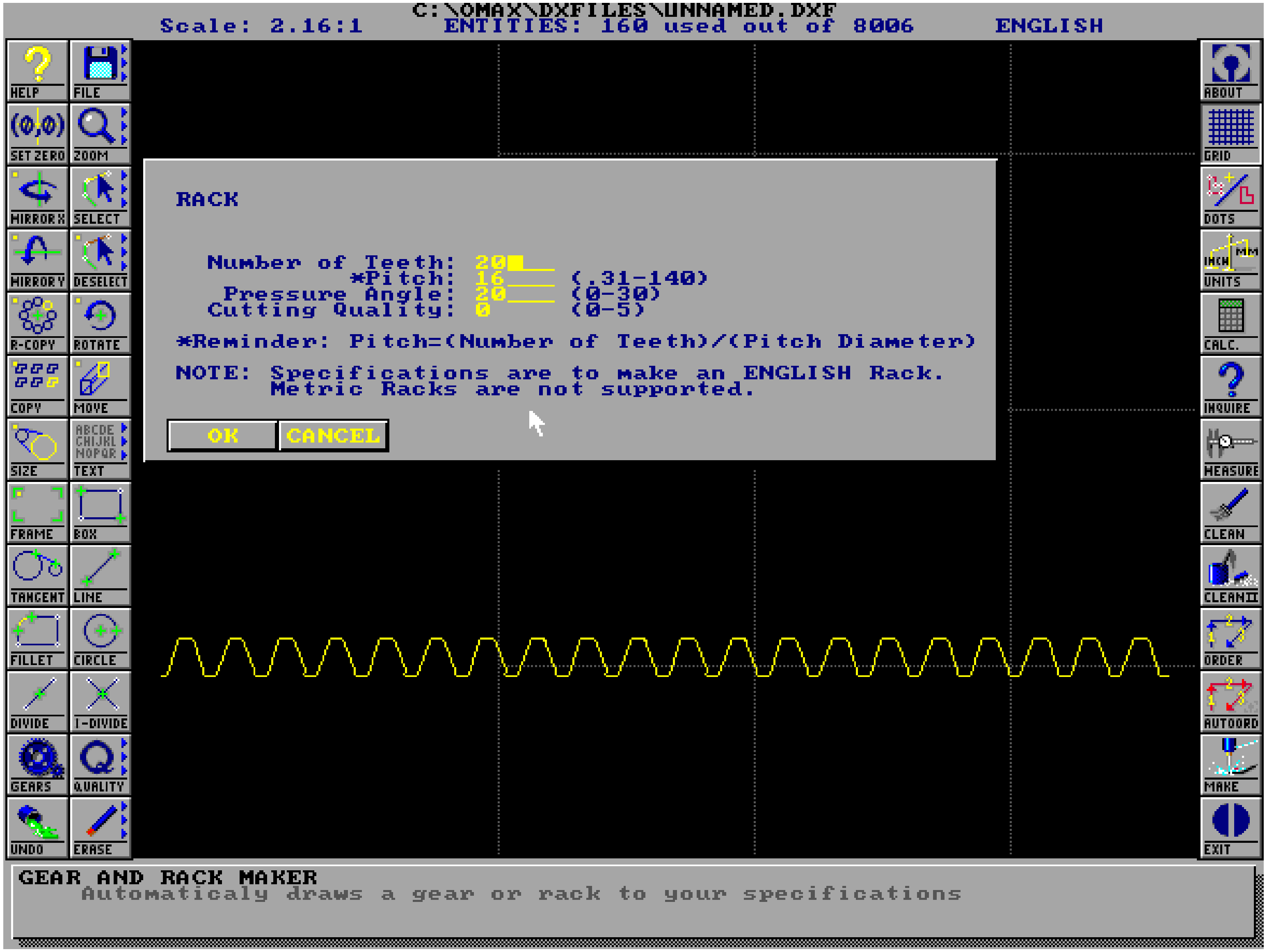


This section on making gears using an Abrasive Waterjet Machining Center™ was created with the generous help of Carl Olson from Omax, Inc. (www.omax.com)

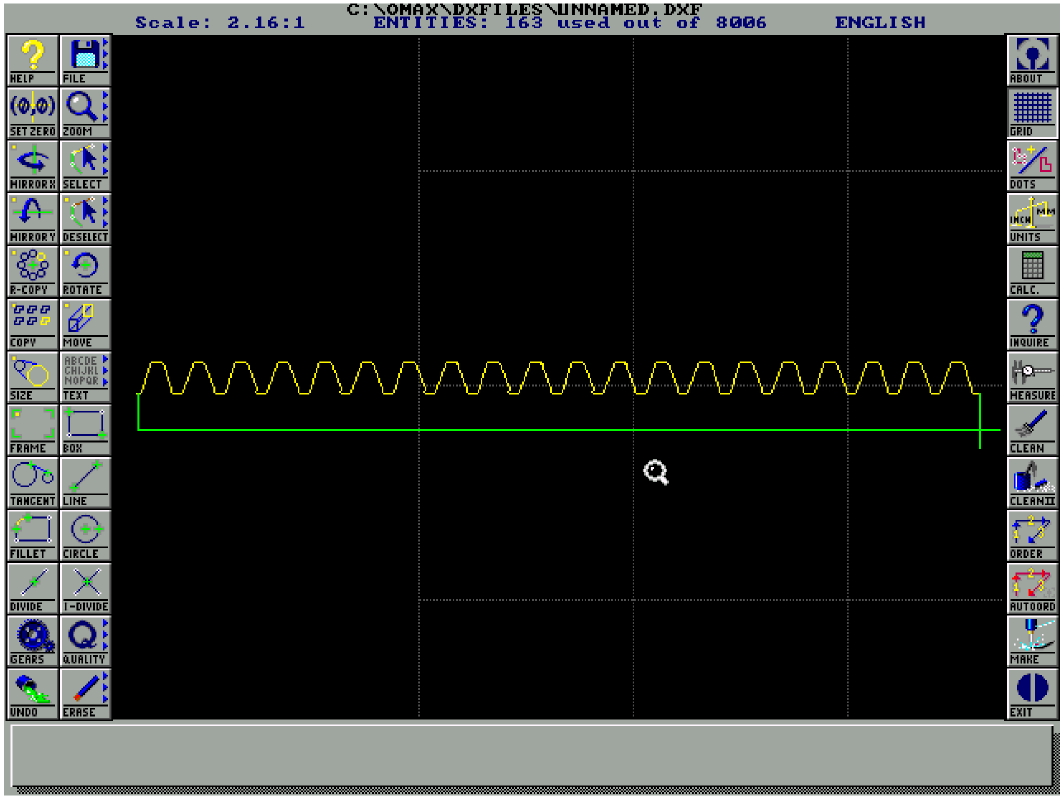




Racks: *Step 1 Define the Rack Parameters*



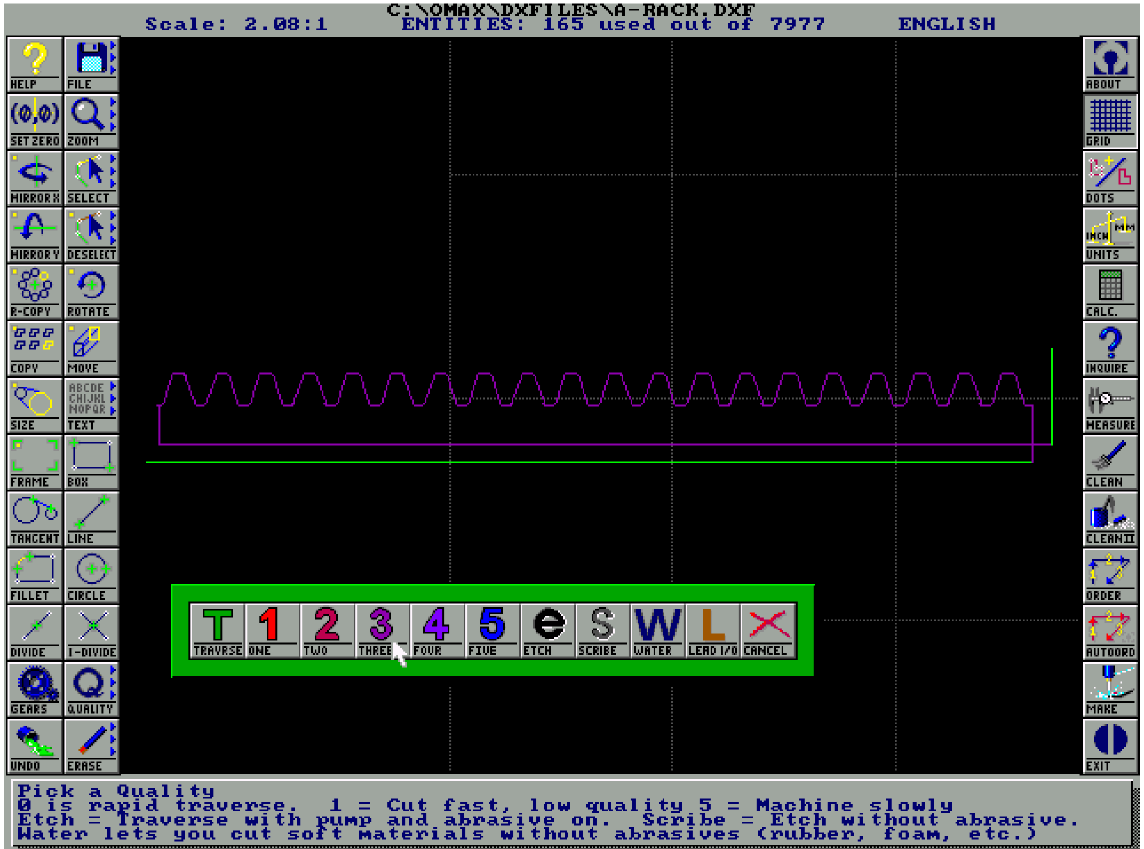
Rack: *Step 2 Add Lines for the Rest of the Rack and Lead-In/out lines*

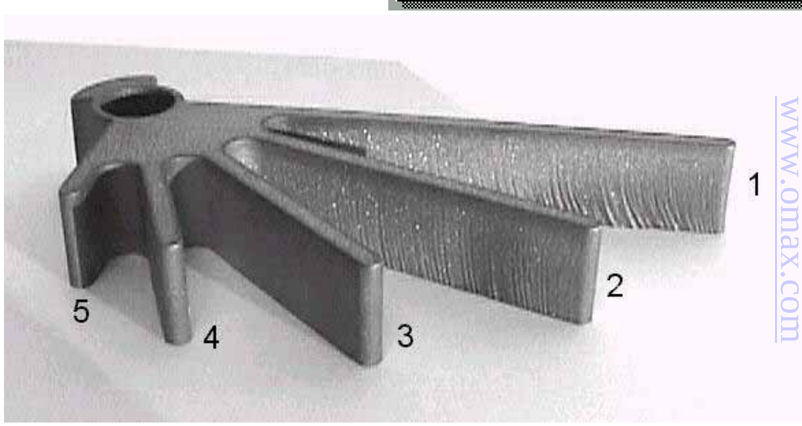


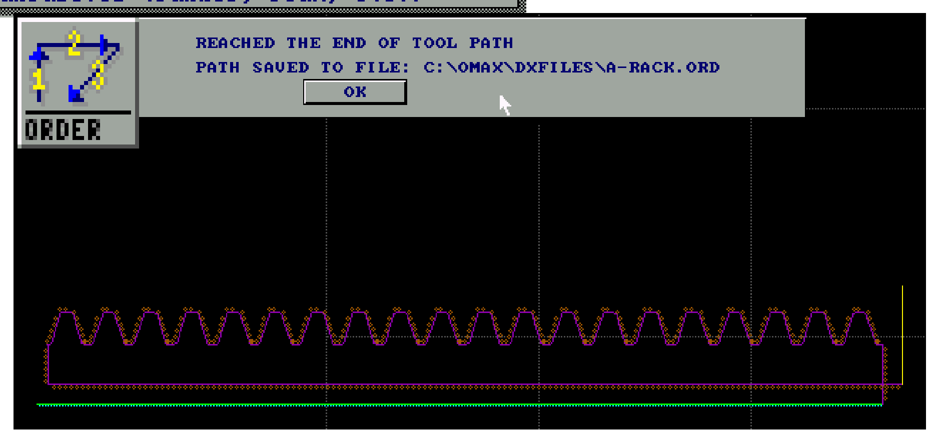
Tip: To draw pure horizontal or vertical lines, hold down the "Shift" key when "free-hand" drawing

Tip: One may also wish to make the rack and the gear as part of the same part path

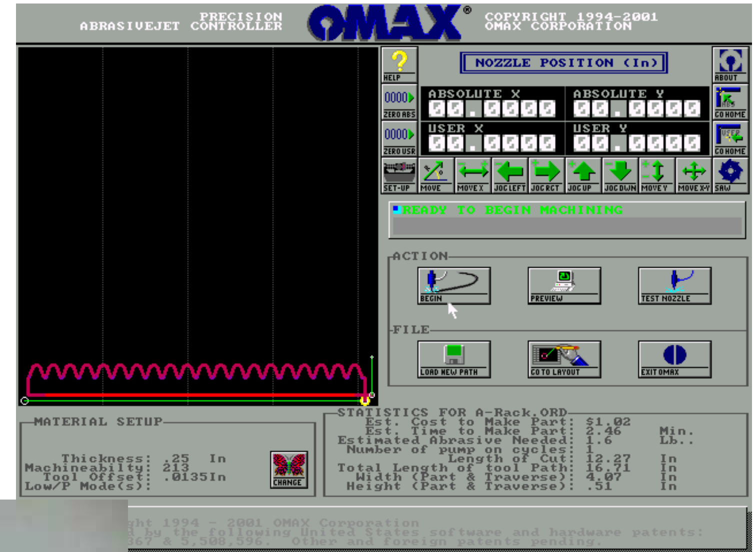
Racks: *Step 3 Define Path Quality & Create Tool Path*







Racks: *Step 5 Make & Voila!*



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