

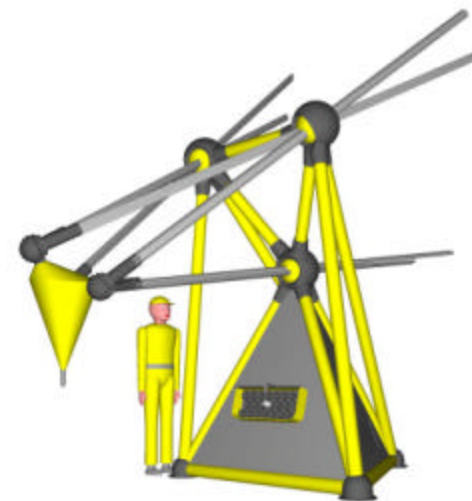
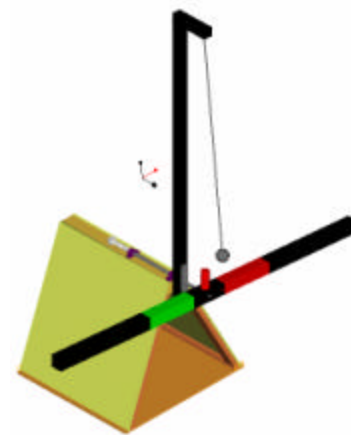
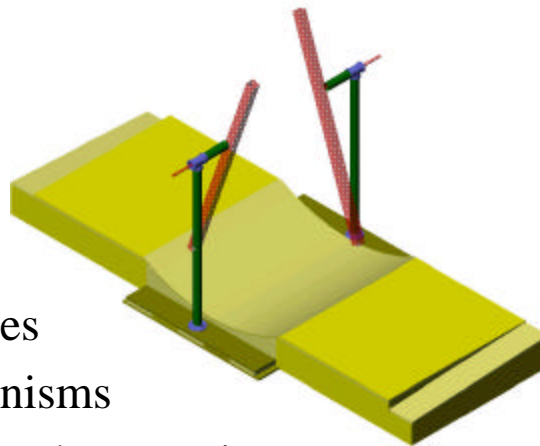
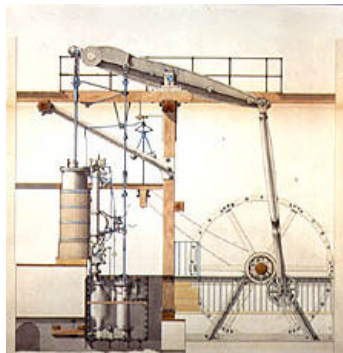


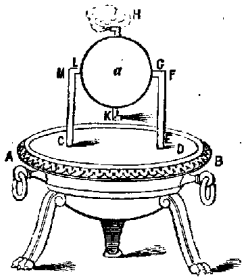
Topic 4 Linkages



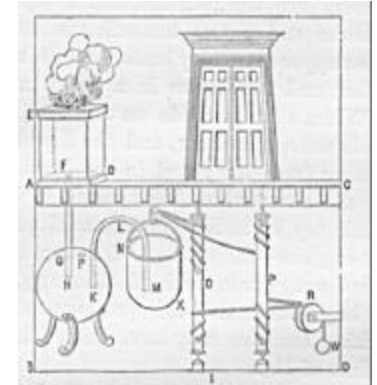
Topics

- History
- Definitions
- Links
- Joints
- Instantaneous Center of Rotation
- 3-Bar Linkages
- 4-Bar Linkages
- 5-Bar Linkages
- 6-Bar Linkages
- Extending Linkages
- Compliant Mechanisms
- Manufacturing & Robust Design
- *Mechanism Mania!*



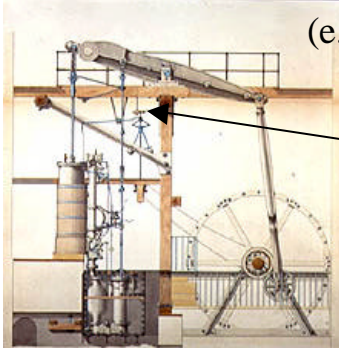


History



- The weaving of cloth gave rise to the need for more complex machines to convert rotary motion from waterwheels to complex motions
- The invention of the steam engine created a massive need for new mechanisms and machines

- Long linear motion travel was required to harness steam power, and machine tools (e.g., planar mills) did not exist



- *James Watt* (1736-1819) applied thermodynamics (though he did not know it) and rotary joints and long links to create efficient straight line motion

- Watt also created the *flyball governor*, the first servomechanism, which made steam engines safe and far more useful

- *Leonard Euler* (1707-1783) was one of the first mathematicians to study the mathematics of linkage design (synthesis)

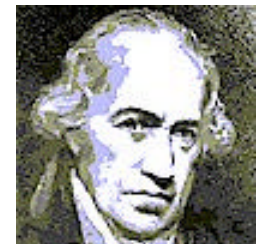
- Most linkages are *planar*, their motion is confined to a plane

- The generic study of linkage motions, *planar* and *spatial*, is called *screw theory*

- *Sir Robert Stawell Ball* (1840-1913) is considered the father of screw theory

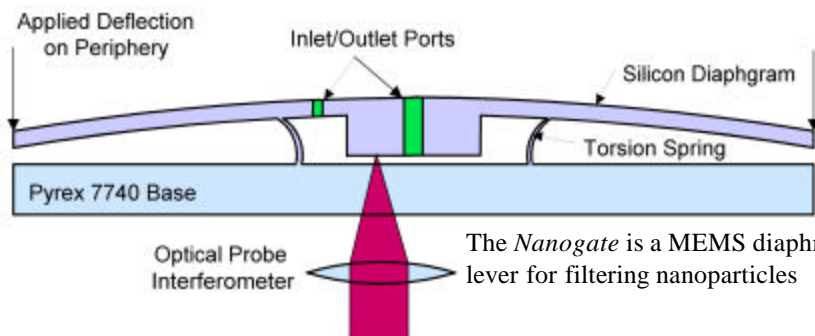
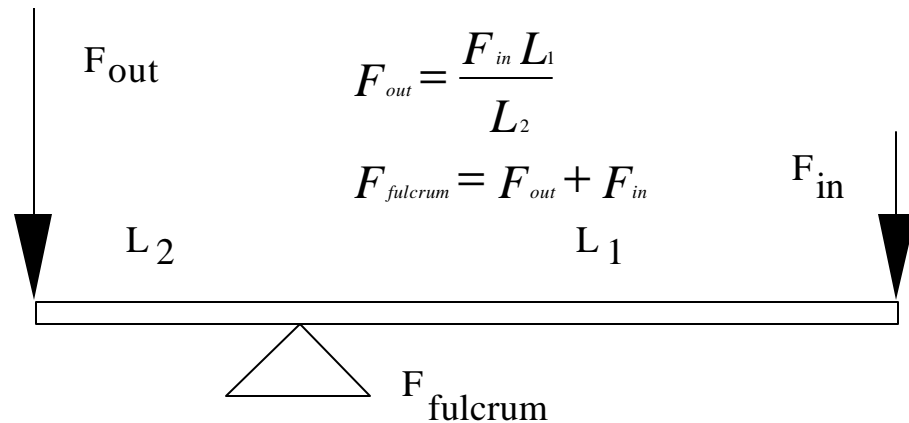
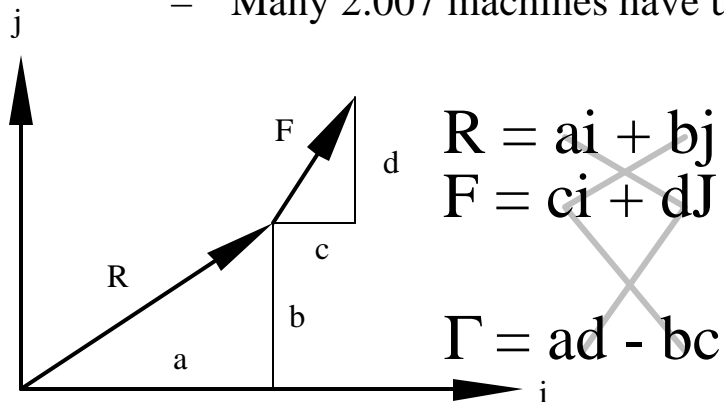
- There is a HUGE variety of linkages that can accomplish a HUGE variety of tasks

- It takes an entire course just to begin to appreciate the finer points of linkage design



The First Mechanism: *The Lever*

- A lever can be used with a fulcrum (pivot) to allow a small force moving over a large distance to create a large force moving over a short distance...
 - When one considers the means to input power, a lever technically becomes a 4-bar linkage
- The forces are applied through pivots, and thus they may not be perpendicular to the lever
 - Torques about the fulcrum are thus the best way to determine equilibrium, and torques are best calculated with vector cross product
 - Many 2.007 machines have used levers as flippers to assist other machines onto their backs...



The Nanogate is a MEMS diaphragm-type lever for filtering nanoparticles

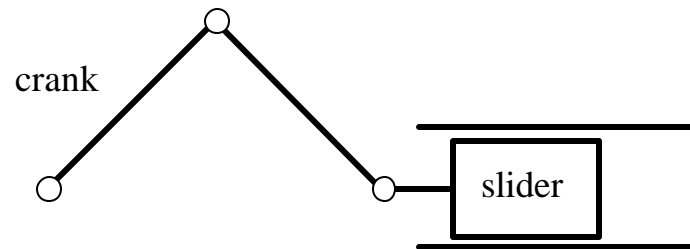


Definitions

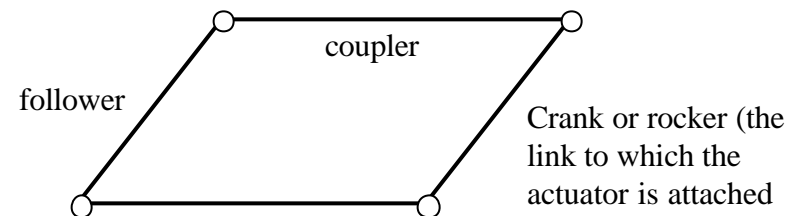
- *Linkage*: A system of *links* connected at *joints* with rotary or linear bearings
 - *Joint (kinematic pairs)*: Connection between two or more links at their nodes, which allows motion to occur between the links
 - *Link*: A rigid body that possess at least 2 nodes, which are the attachment points to other links
- *Degrees of Freedom (DOF)*:
 - The number of input motions that must be provided in order to provide the desired output, OR
 - The number of independent coordinates required to define the position & orientation of an object
 - For a planar mechanism, the degree of freedom (mobility) is given by *Gruebler's Equation*:

$$F = 3(n - 1) - 2f_1$$

- n = Total number of links (including a fixed or single ground link)
- f_1 = Total number of joints (some joints count as $f = 1/2, 1, 2$, or 3)
 - Example: Slider-crank $n = 4, f_1 = 4, F = 1$
 - Example: 4-Bar linkage $n = 4, f_1 = 4, F = 1$
 - The simplest linkage with at least one degree of freedom (motion) is thus a 4-bar linkage!
 - A 3-bar linkage will be rigid, stable, not moving unless you bend it, break it, or pick it up and throw it!



4 links (including ground), 4 joints



4 links, 4 joints

Links

- Binary Link: Two nodes:



- Ternary Link: Three nodes:



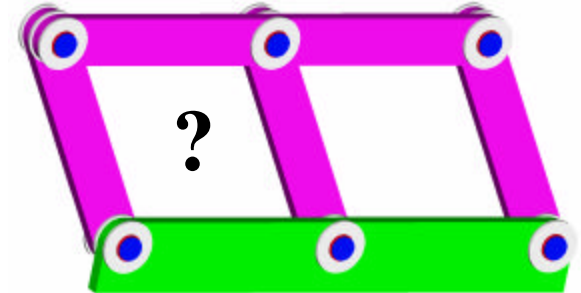
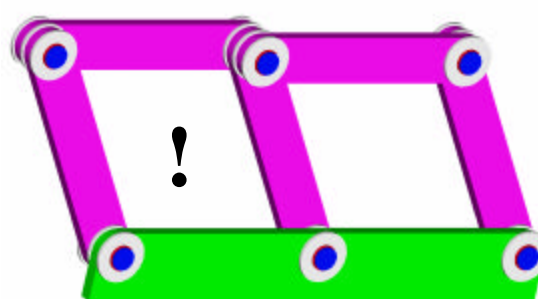
- Quaternary Link: Four nodes:



- Pentanary Link: Five nodes!
(*Can you find it?!*)



Can you identify all the links?



Joints: *Single Degree-of-Freedom*



- *Lower pairs (first order joints) or full-joints* (counts as $f = 1$ in Gruebler's Equation) have one degree of freedom (only one motion can occur):

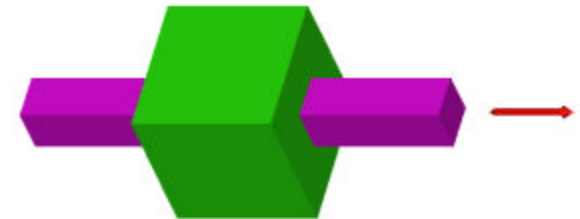
- *Revolute (R)*

- Also called a pin joint or a pivot, take care to ensure that the axle member is firmly anchored in one link, and bearing clearance is present in the other link
- Washers make great thrust bearings
- Snap rings keep it all together
- A *rolling contact* joint also counts as a one-degree-of-freedom revolute joint



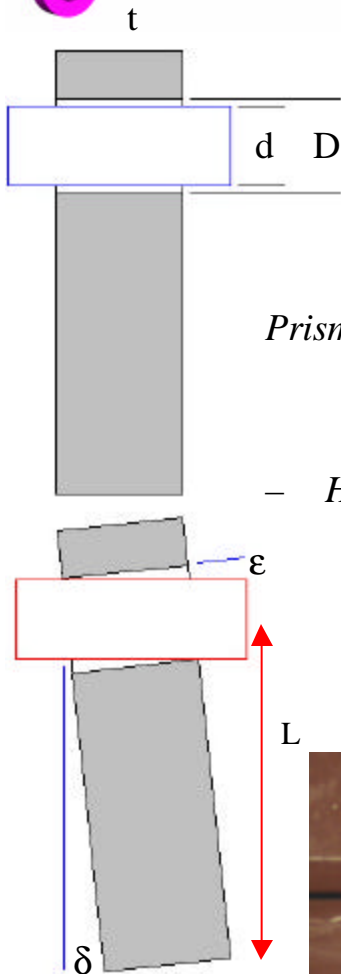
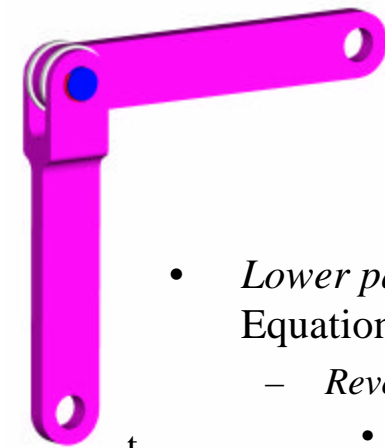
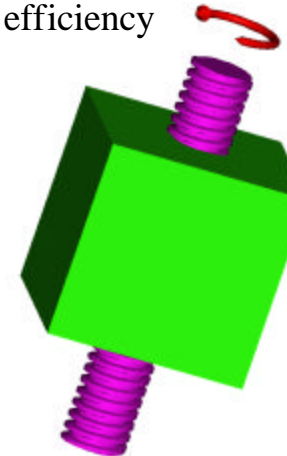
- *Prismatic (P)*

- Also called a slider or sliding joint, beware Saint-Venant!



- *Helical (H)*

- Also called a screw, beware of thread strength, friction and efficiency

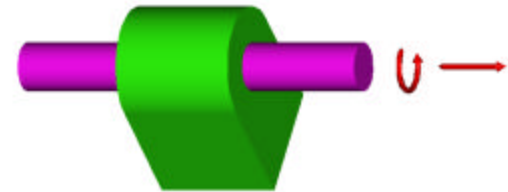


Joints: *Multiple Degree-of-Freedom*

- *Lower Pair joints with multiple degrees of freedom:*

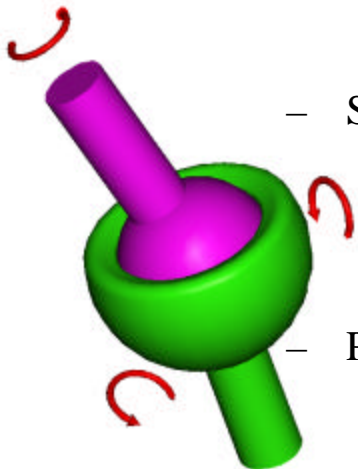
- Cylindrical (C) 2 DOF

- A *multiple-joint* ($f = 2$ in Gruebler's Equation)



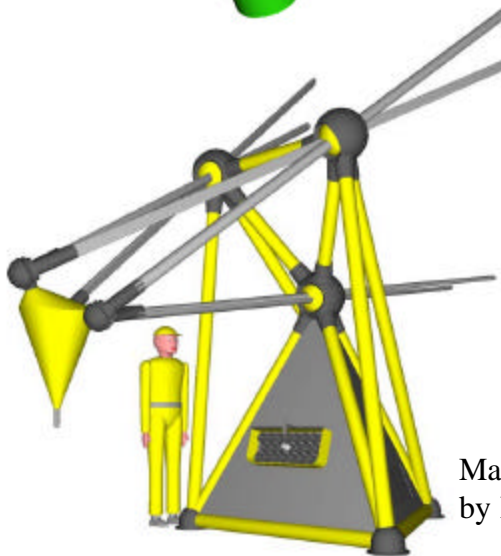
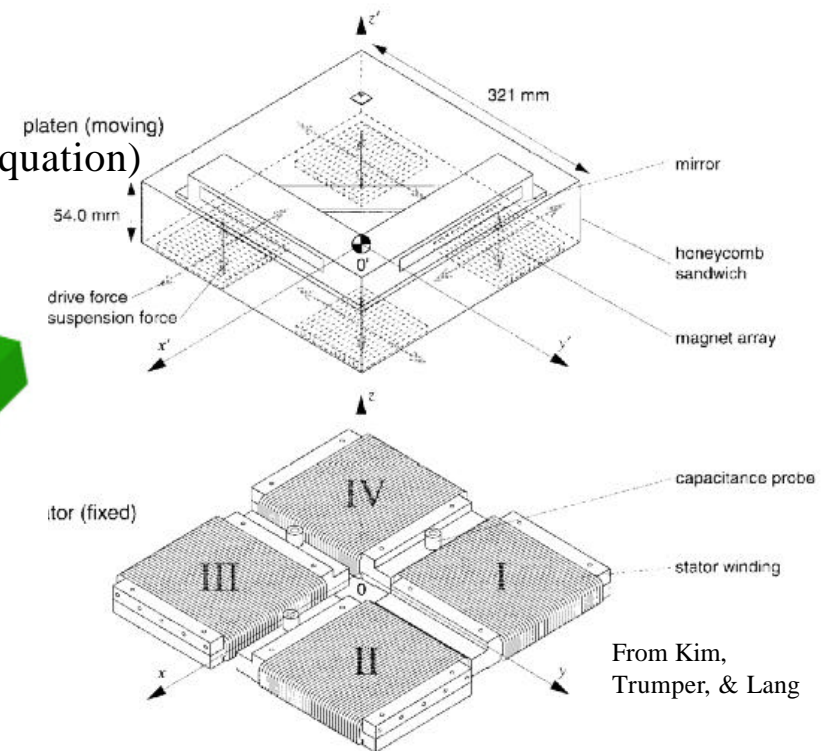
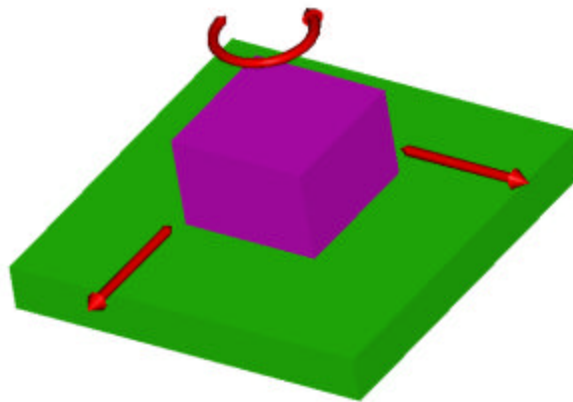
- Spherical (S) 3 DOF

- A *multiple-joint* not used in planar mechanisms ($f = 3$ in Gruebler's Equation)



- Planar (F) 3 DOF

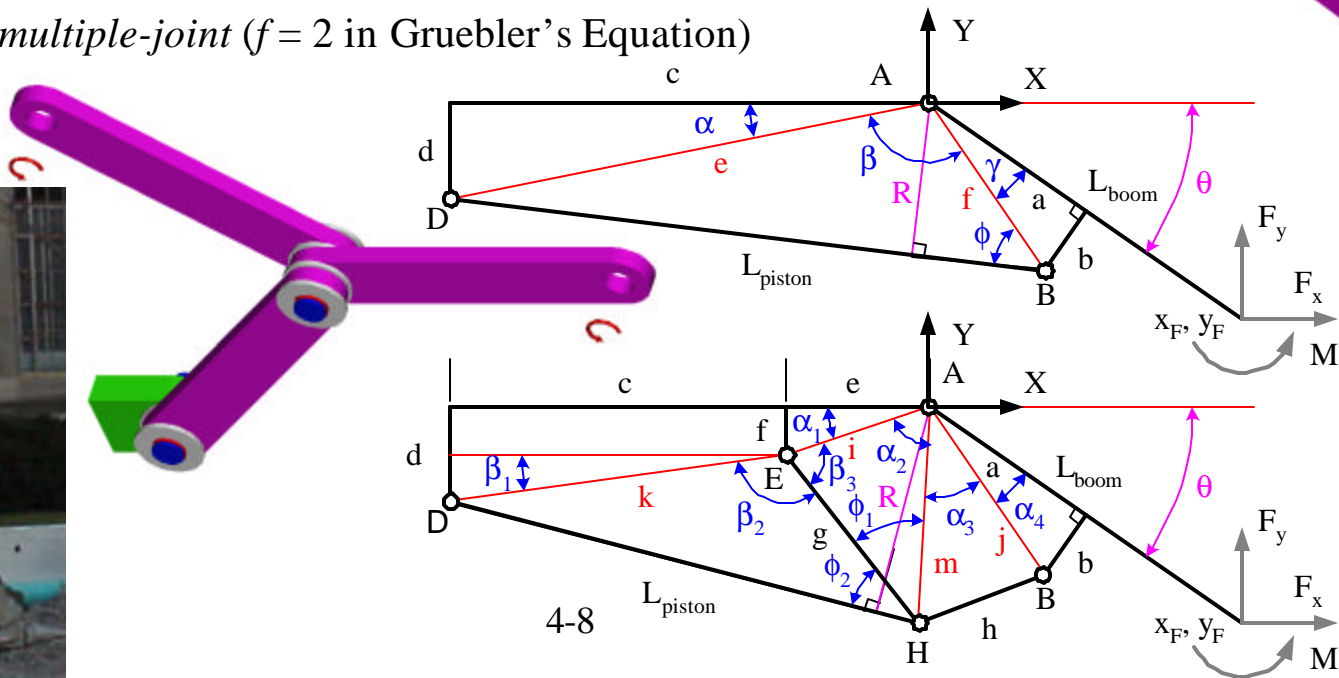
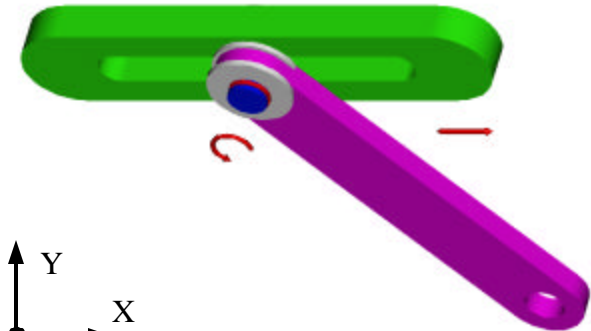
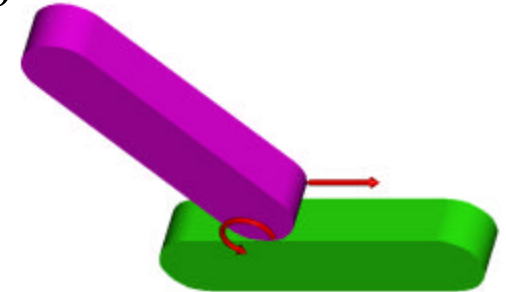
- A *multiple-joint* ($f = 3$ in Gruebler's Equation)



Machine concept
by Peter Bailey

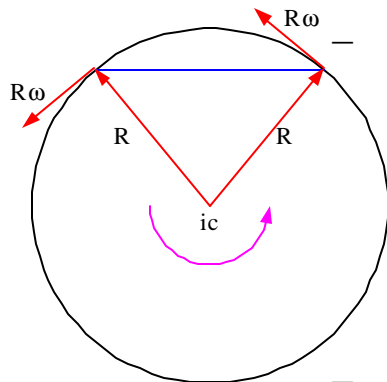
Joints: *Higher Pair Multiple Degree-of-Freedom*

- *Higher Pair* joints with multiple degrees of freedom:
 - Link against a plane
 - A force is required to keep the joint closed (force closed)
 - A *half-joint* ($f = 0.5$ in Gruebler's Equation)
 - The link may also be pressed against a rotating cam to create oscillating motion
 - Pin-in-slot
 - Geometry keeps the joint closed (form closed)
 - A *multiple-joint* ($f = 2$ in Gruebler's Equation)
 - Second order pin joint, 3 links joined, 2-DOF
 - A *multiple-joint* ($f = 2$ in Gruebler's Equation)

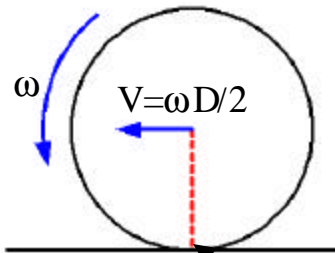


Instantaneous Center of Rotation

- The *instant center* for a point on a moving body is the center of the circular arc that coincides with the path of the point for an infinitesimal portion of the path

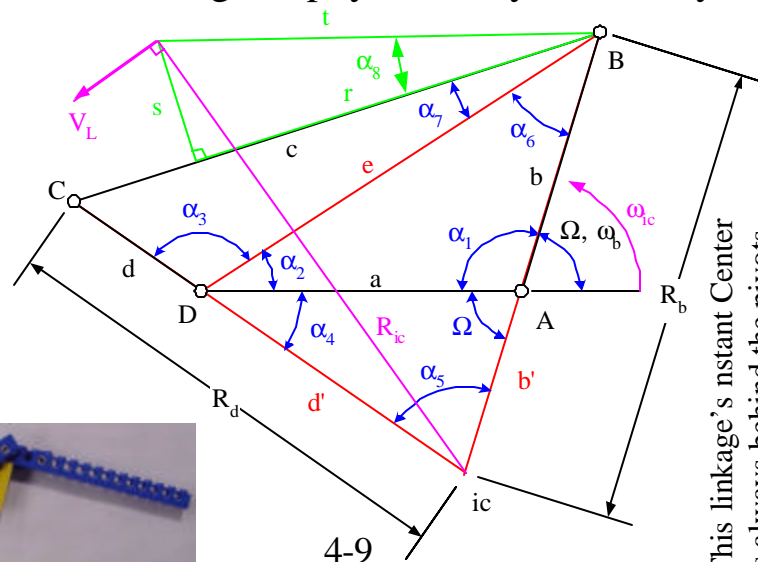


- For a 4-bar linkage, draw lines through the crank and follower pivots, and the point at which the lines intersect is called the *instant center*
 - The velocity of any point on the coupler at any point is perpendicular to an imaginary line from the instant center to the point of interest
 - The instant center is used to determine the linear and angular velocity and acceleration of the coupler's center of mass or the coupler point
- If the instant center is coincident with a joint on the coupler, the linkage can become unstable and can lock up

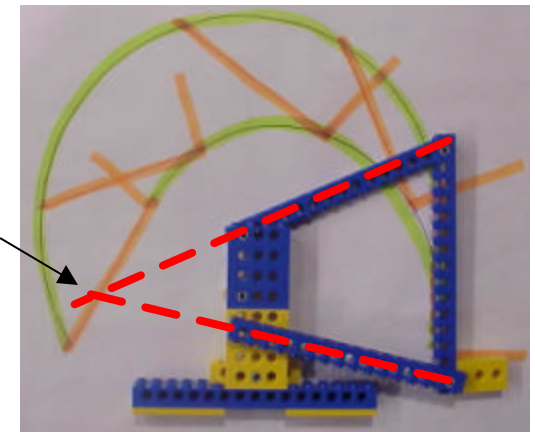
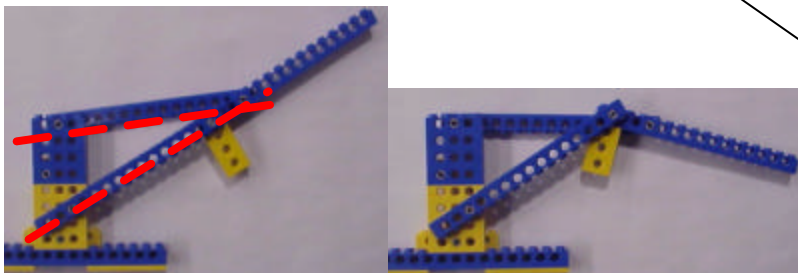


Rolling wheel
ground pivot &
Instant Center

- A sketch model is a great physical way to check your linkage design!

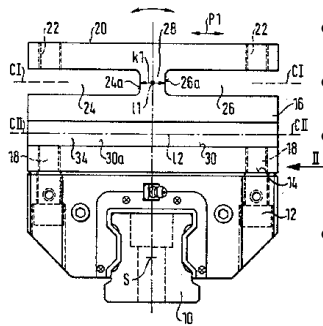


This linkage's Instant Center
is always behind the pivots



3-Bar Linkages: Accommodating Bearing Misalignment

- A 3-Bar linkage system can minimize the need for precision alignment of bearing ways
 - Accommodates change in way parallelism if machine foundation changes
 - US Patent (4,637,738) now available for royalty-free public use



US patent 5,176,454

- Round shafts are mounted to the structure with reasonable parallelism
- One bearing carriage rides on the first shaft, and it is bolted to the bridge structure risers
- One bearing carriage rides on the second shaft, and it is connected to the bridge structure risers by a spherical bearing or a flexure
- Alignment errors (pitch and yaw) between the round shafts are accommodated by the spherical or flexural bearing
- Alignment errors (δ) between the shafts are accommodated by roll (θ) of the bearing carriage
- Vertical error motion (Δ) of the hemisphere is a second order effect
- Example: $\delta = 0.1''$, $H = 4''$, $\theta = 1.4$ degrees, and $\Delta = 0.0012''$
- Abbe's Principle is used to the advantage of the designer!

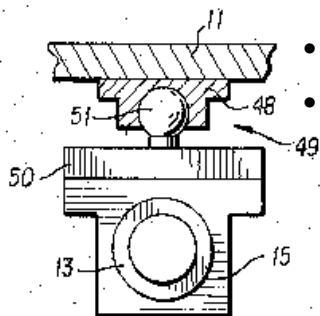


FIG. 9

US patent 4,637,738

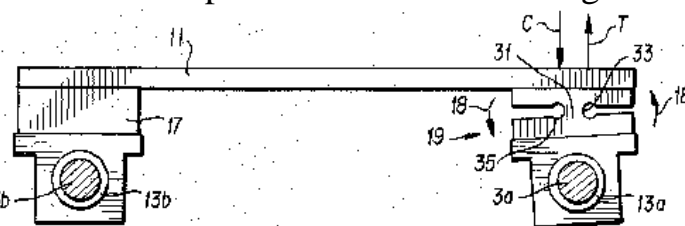
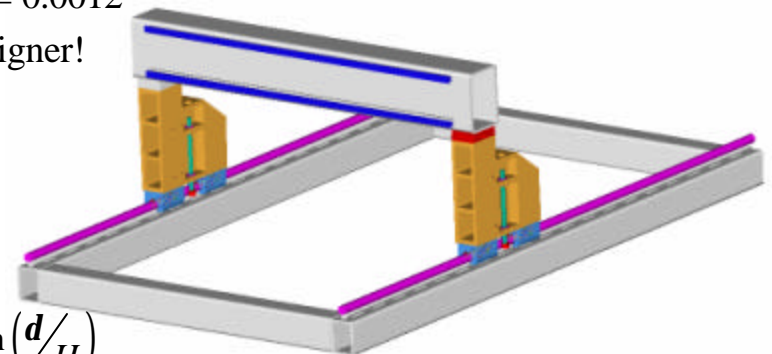


FIG. 3

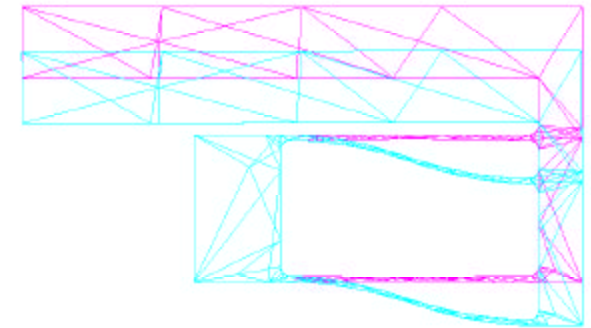
$$q = \arcsin\left(\frac{d}{H}\right)$$

$$\Delta = H(1 - \cos q) \approx \frac{d^2}{2H}$$

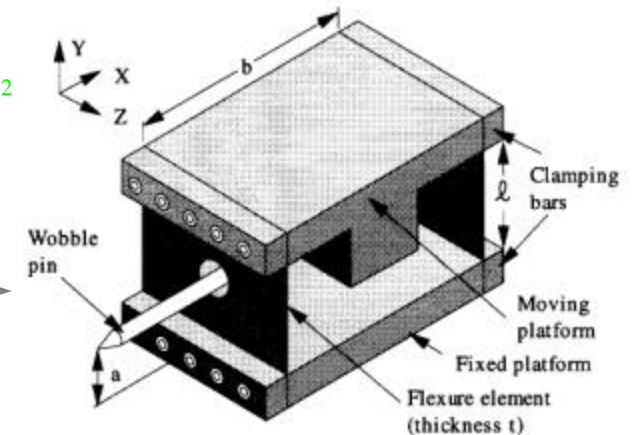
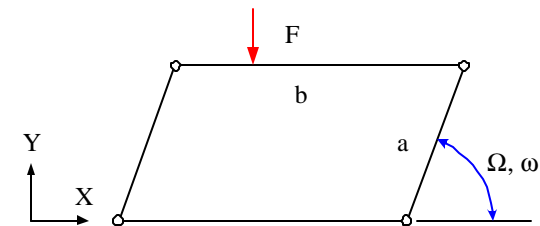
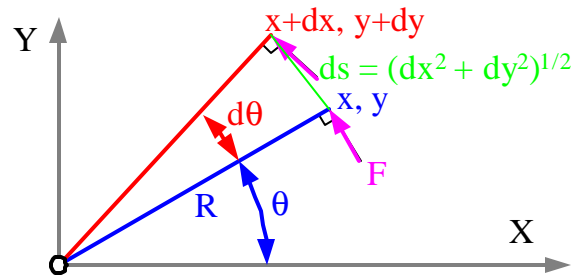
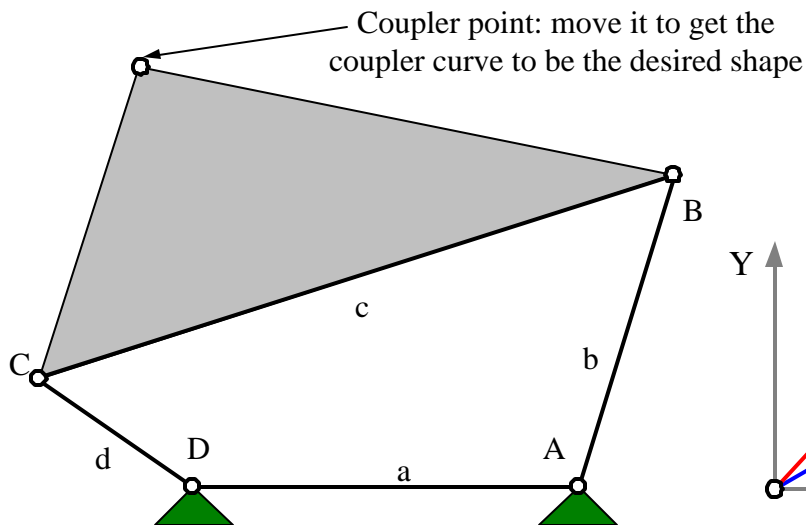




4-Bar Linkages

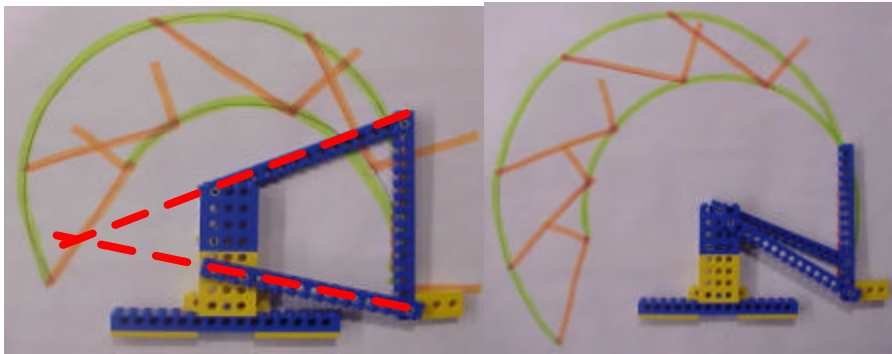
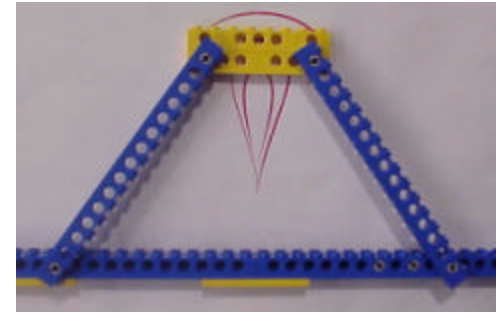


- 4-Bar linkages are commonly used for moving platforms, clamping, and for buckets and moving platforms
 - They are perhaps the most common linkage
 - They are relatively easy to create
 - One cannot always get the motion and force one wants
 - In that case, a 5-Bar linkage may be the next best thing

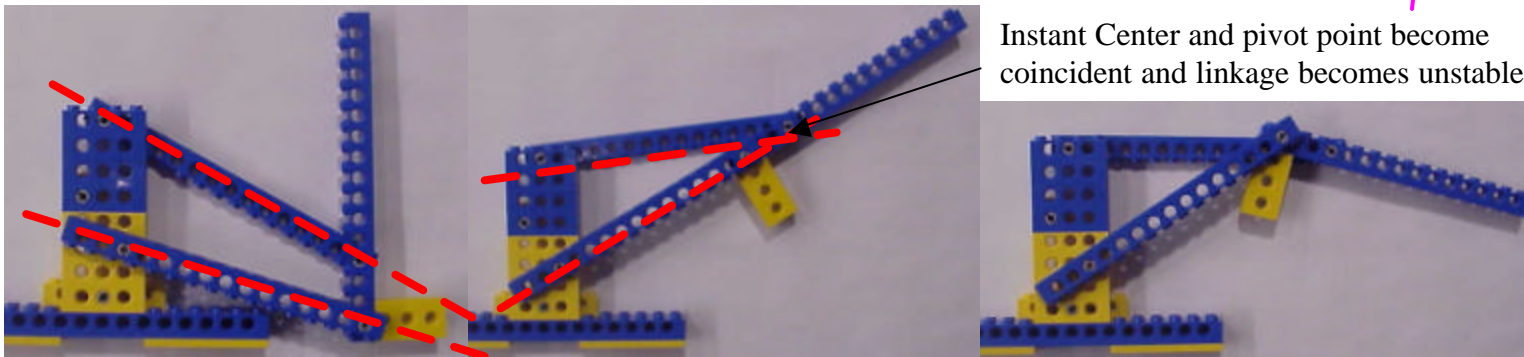
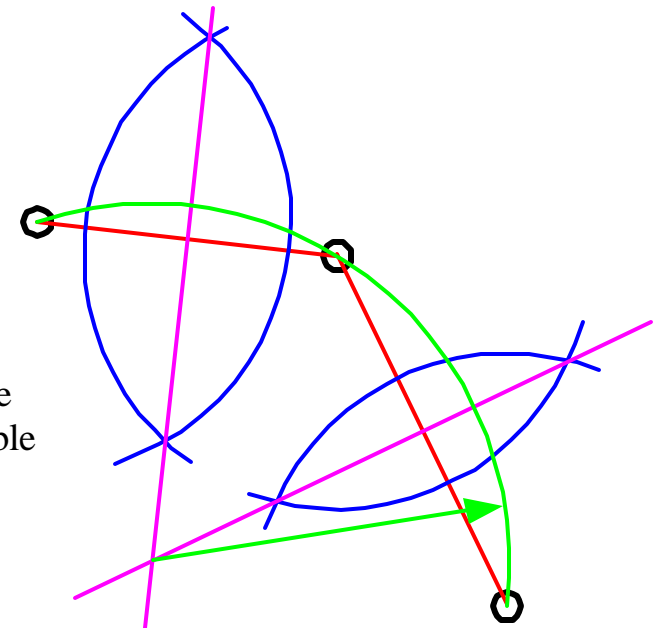


4-Bar Linkages: *Kinematic Synthesis*

- 4-Bar linkage motion can be developed using *kinematic synthesis*:
 - 3 Point Circle Construction
 - Precision Point Method
 - 3 Precision Point Example
 - Loader Example
 - Experimentation

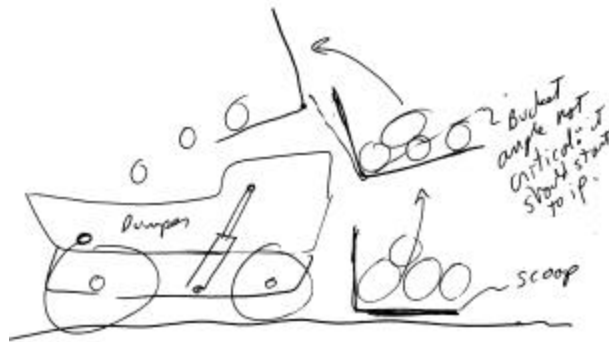
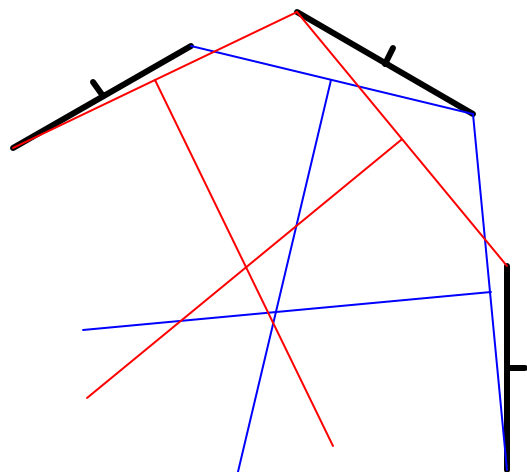
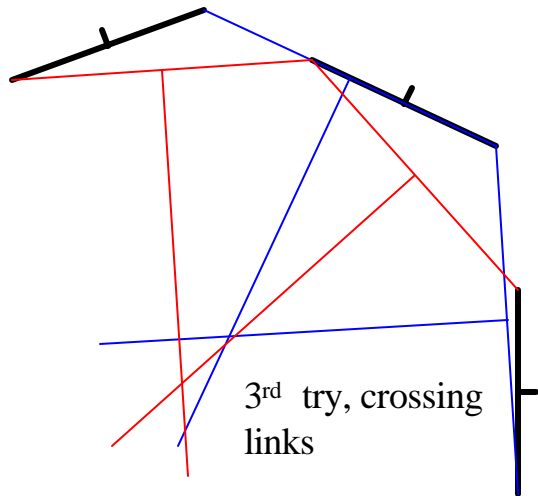


Apply reversal to the geometry and unstable becomes stable!

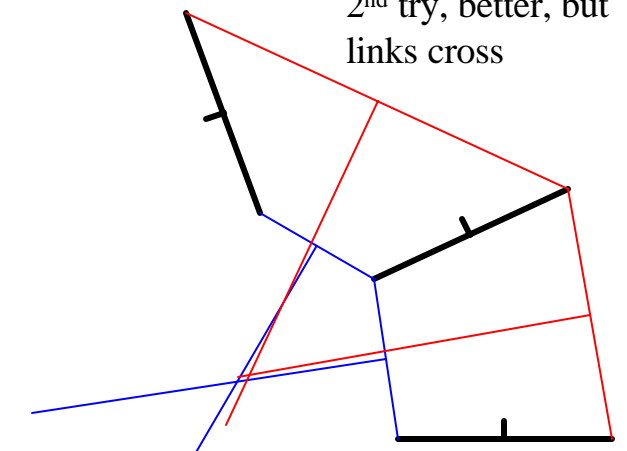
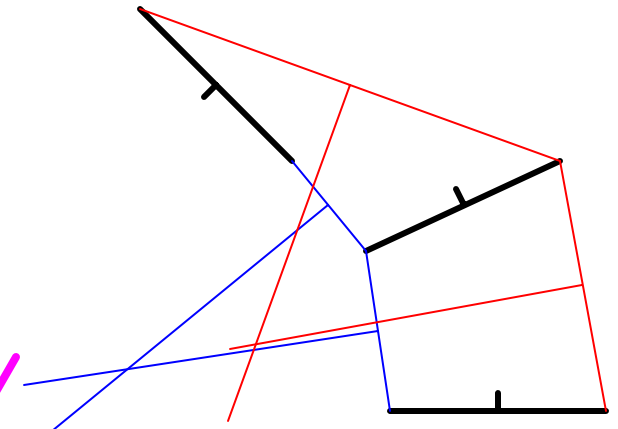
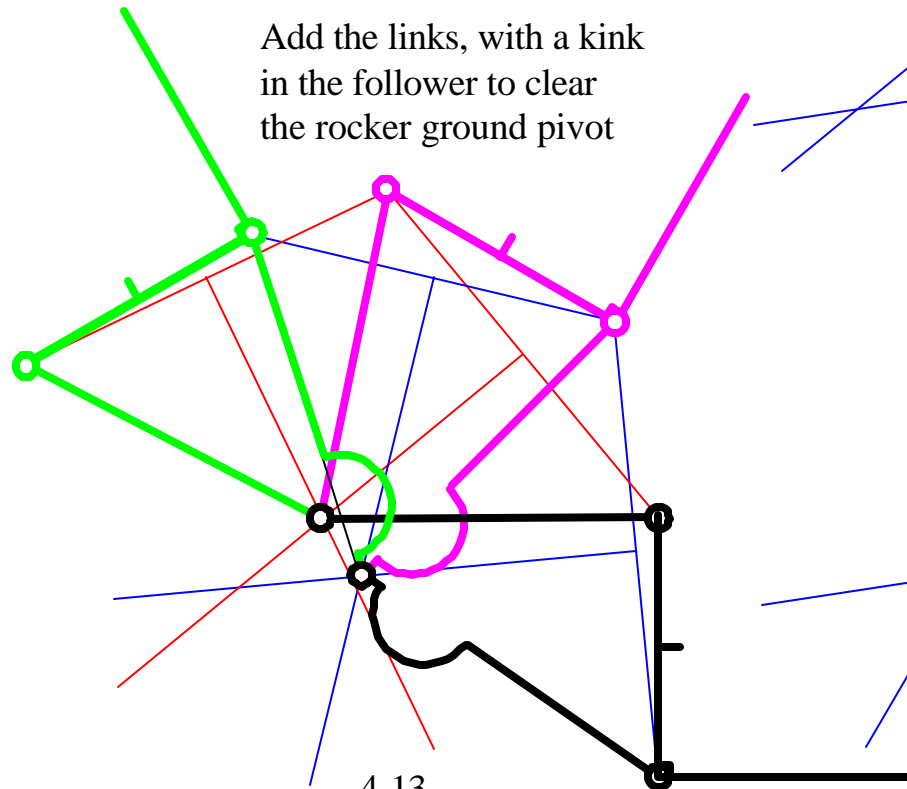


Instant Center and pivot point become coincident and linkage becomes unstable

Kinematic Synthesis: 3 Precision Point Example



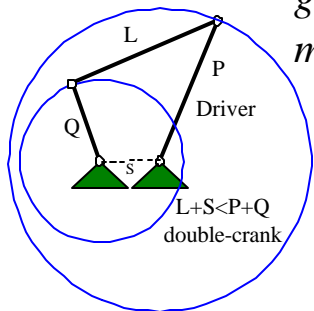
Add the links, with a kink in the follower to clear the rocker ground pivot



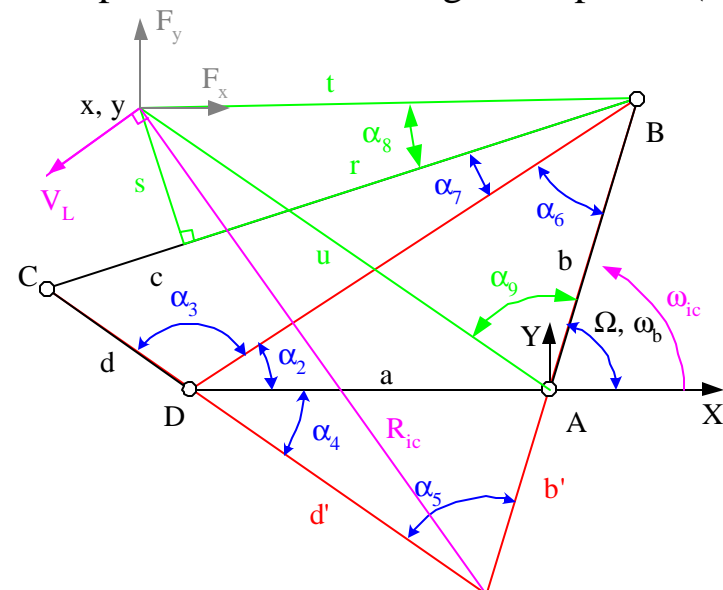
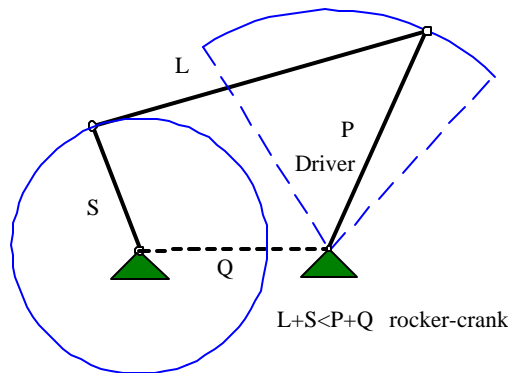
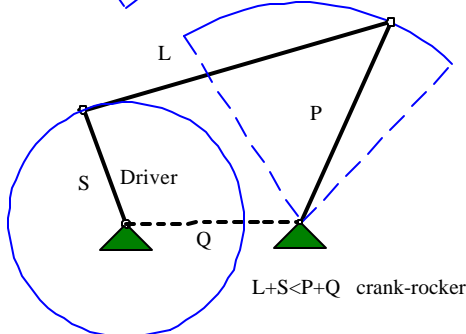
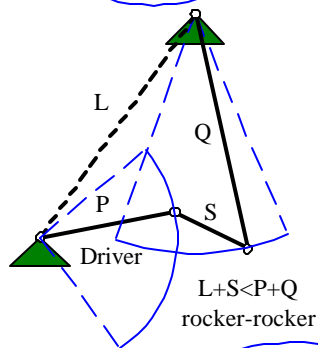
Kinematic Synthesis: *Analysis*

- Code or a spreadsheet can be written to analyze the a general 4-bar linkage, but types of motion can be anticipated using the Grashof criteria:

- The sum of the shortest (S) and longest (L) links of a planar four-bar linkage cannot be greater than the sum of the remaining two links (P, Q) if there is to be continuous relative motion between two links*

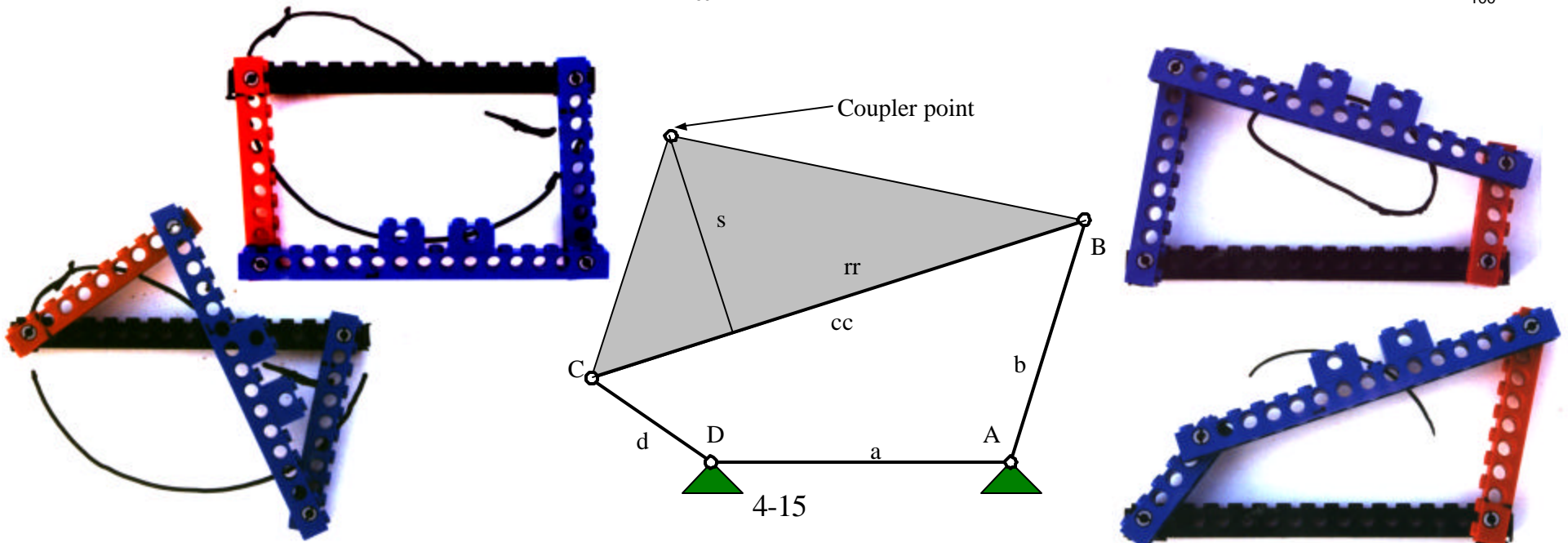
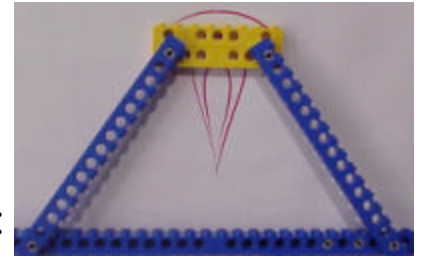
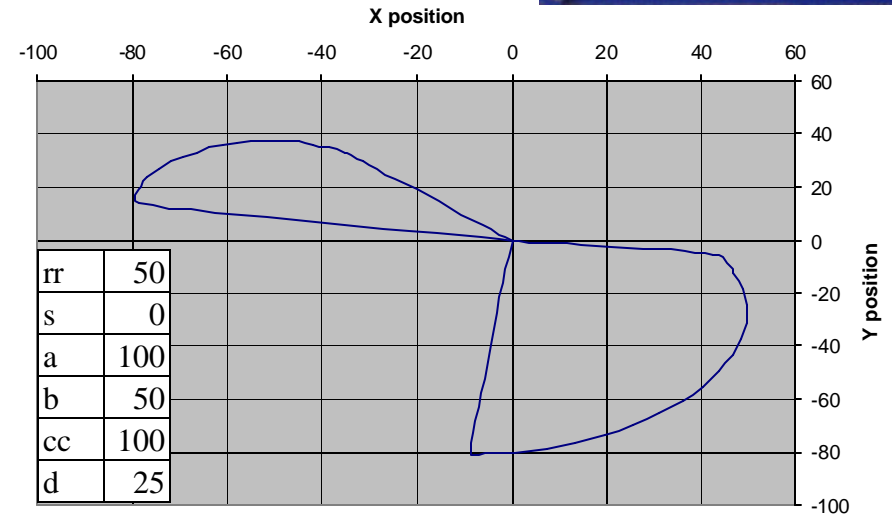
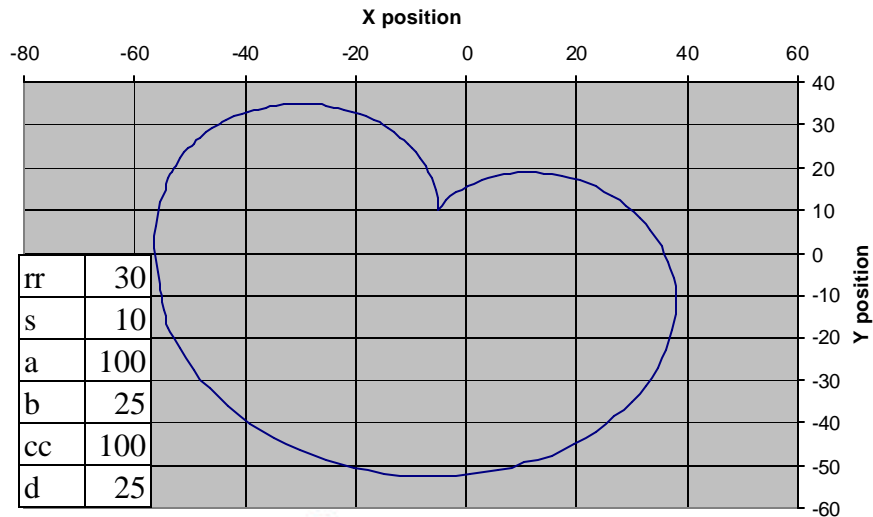


- If $L + S < P + Q$, four *Grashof* mechanisms exist: crank-rocker, double-crank, rocker-crank, double-rocker
 - If $L + S = P + Q$, the same four mechanisms exist, but, change-point condition occurs where the centerlines of all links become colinear and the mechanism can toggle
 - If $L + S > P + Q$, non-Grashof triple-rocker mechanisms exist, depending on which is the ground link, but continuous rotation is not possible
 - Geometric inversions* occur when different pivots are made the ground pivots (this is simply an application of reciprocity)



Kinematic Synthesis: *Coupler Curves*

- From the same analysis, the motions of the coupler point can be plotted:

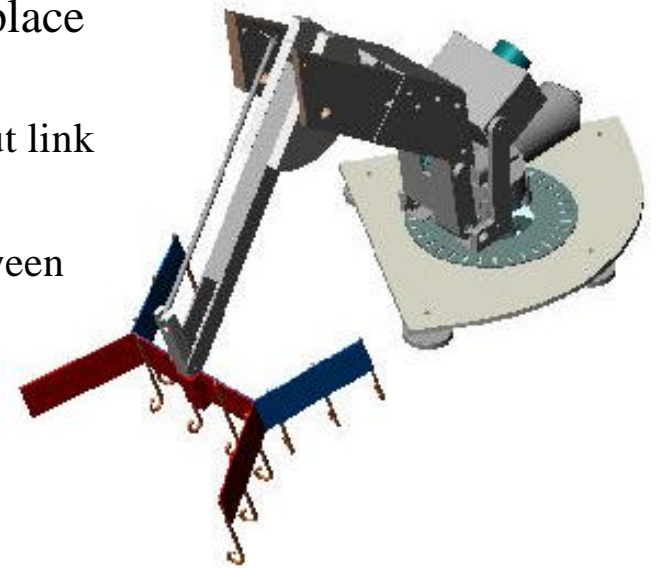




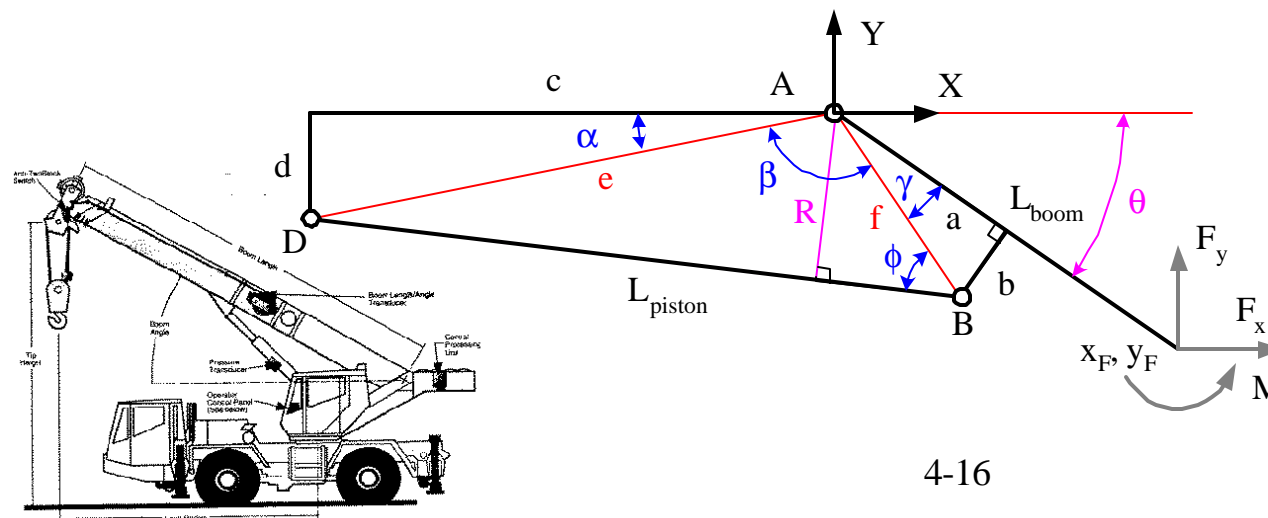
4-Bar Linkages: *Booms*



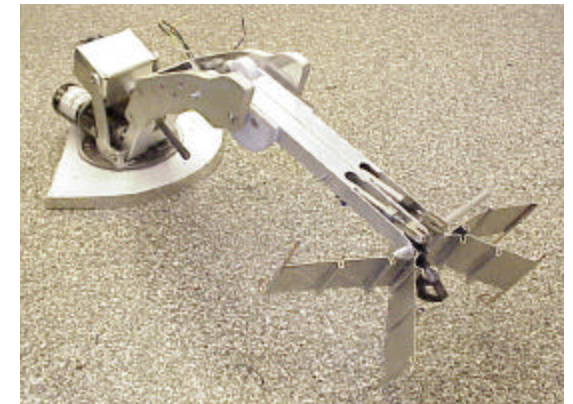
- Linkages for cranes and booms are 4-bar linkages that replace one of the pivot joints with a slider
 - The *boom* is the *follower* even though it is used as the output link
 - The *piston rod* is the “coupler”
 - The *piston cylinder* is the “rocker”, and the connection between the “rocker” and the “coupler” is a *slider joint*
- Link configurations can be determined using parametric sketches, sketch models, or spreadsheets
 - Their simple nature makes them particularly well-suited for development by a spreadsheet



Ayr Muir-Harmony's awesome 2007 machine!



4-16



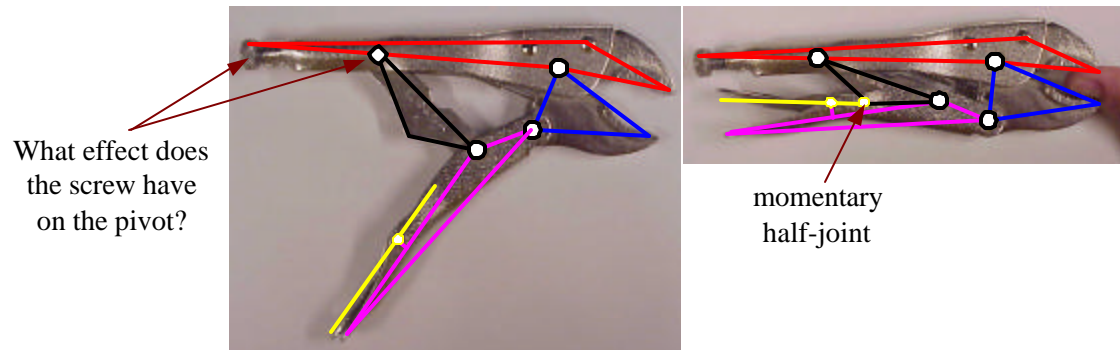
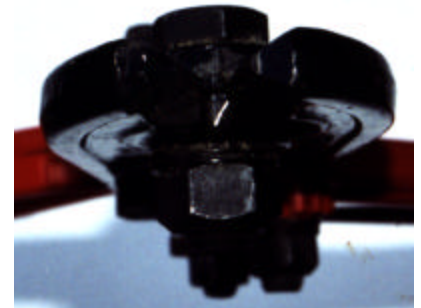
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5-Bar Linkages



- Compare a simple 4-bar linkage for pliers or small bolt cutters to a 5-bar linkage (5 bars, 5 joints, 2 DOF) for bolt cutters
 - The FRs of the pliers are for wide range of motion and modest clamping force



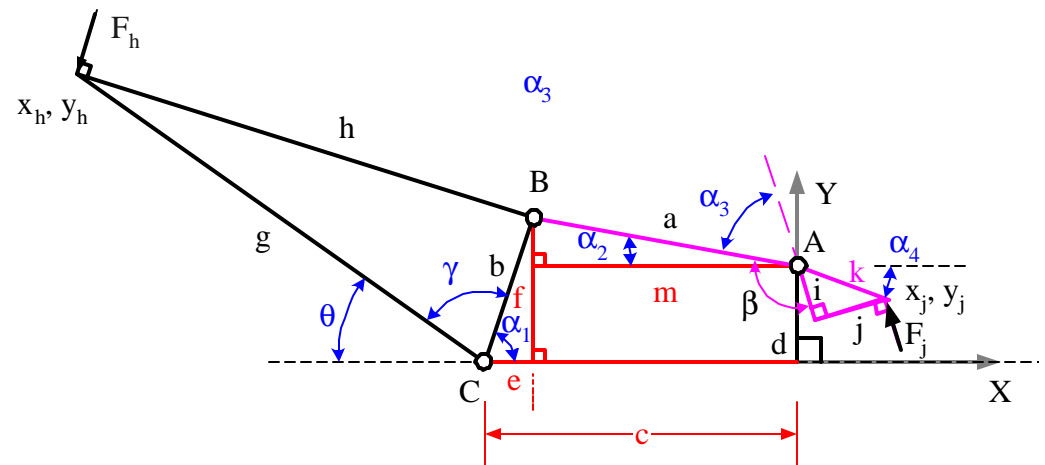
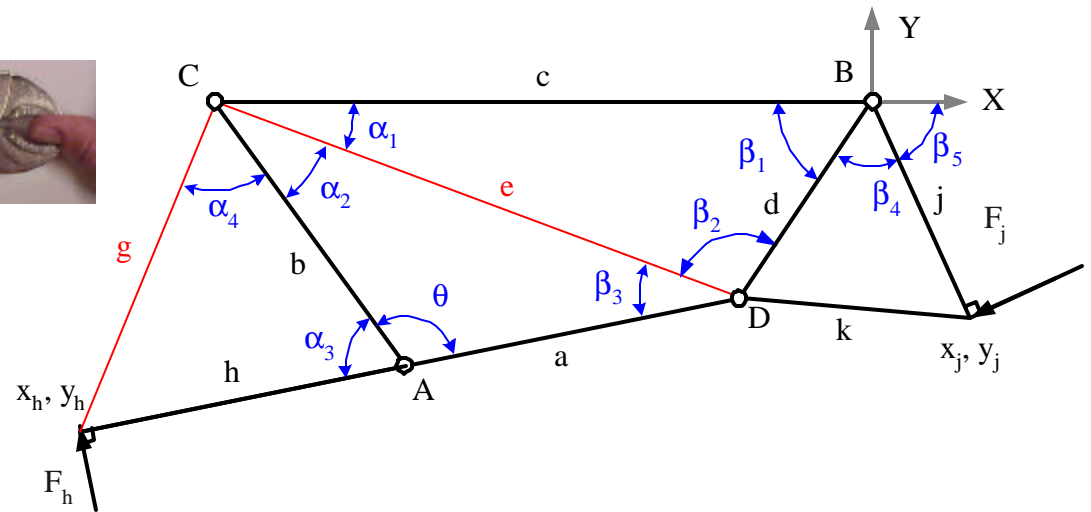
- The FRs of the bolt cutters are for modest motion with extreme force
 - A 5-bar linkage can also act like a toggle mechanism

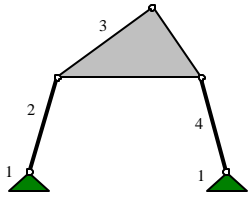


Cutting blade links
Connection link

5-Bar Linkages: *Analysis*

- To determine the force on the jaws caused by a force on the handles, equate the work done:

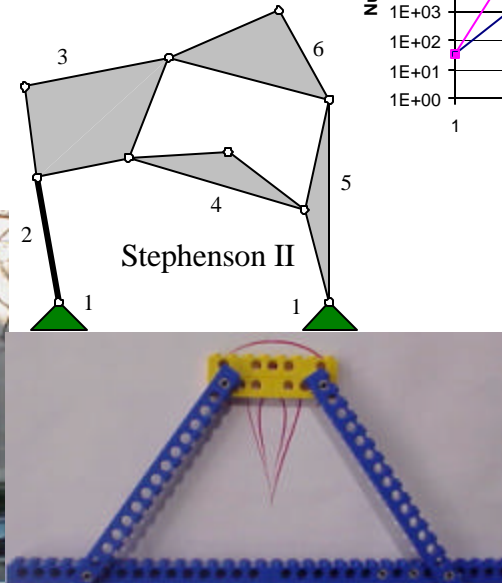
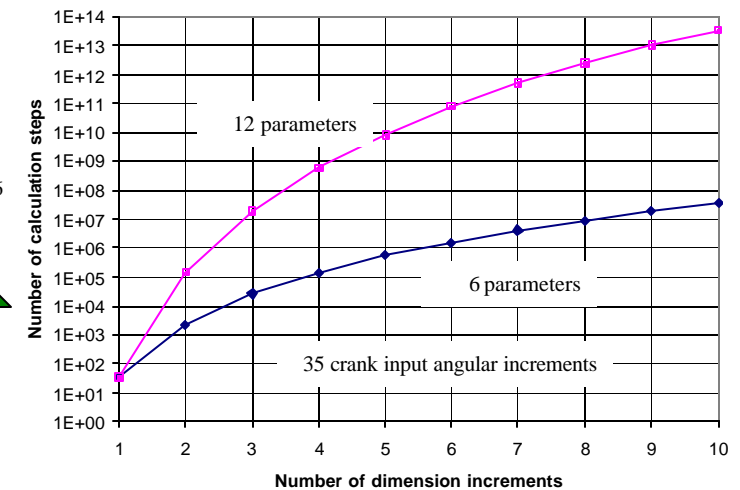
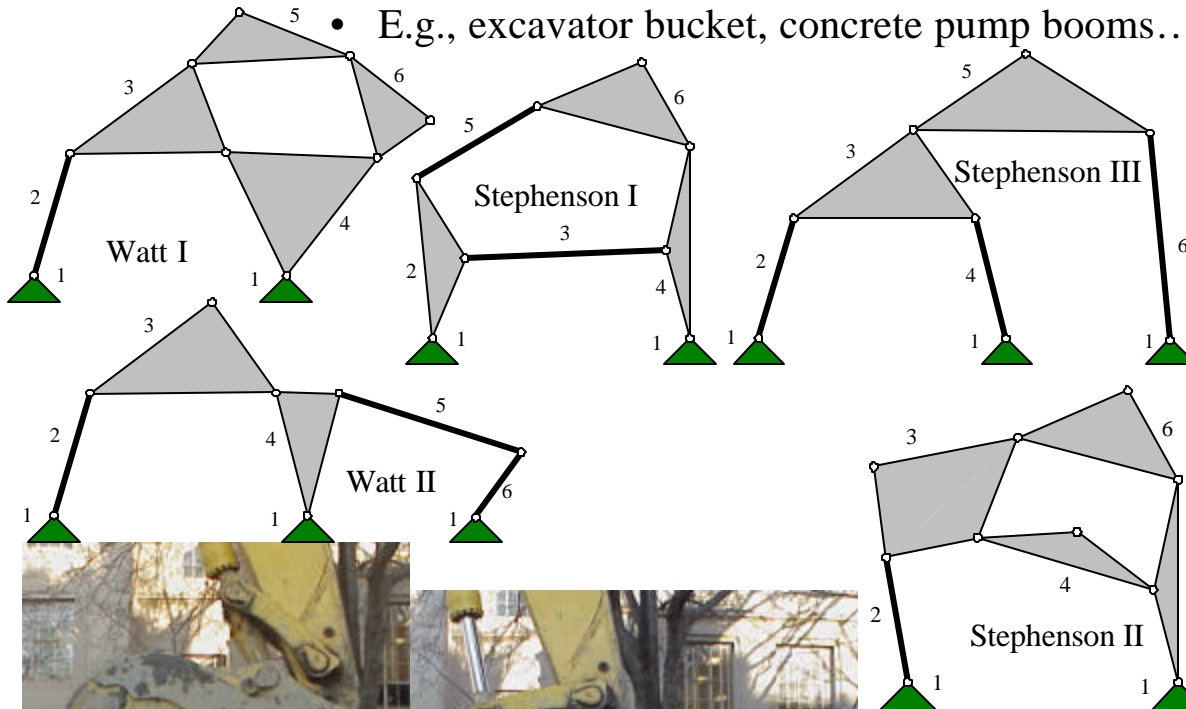




6-Bar Linkages

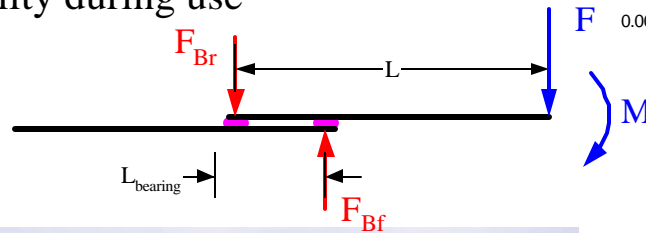
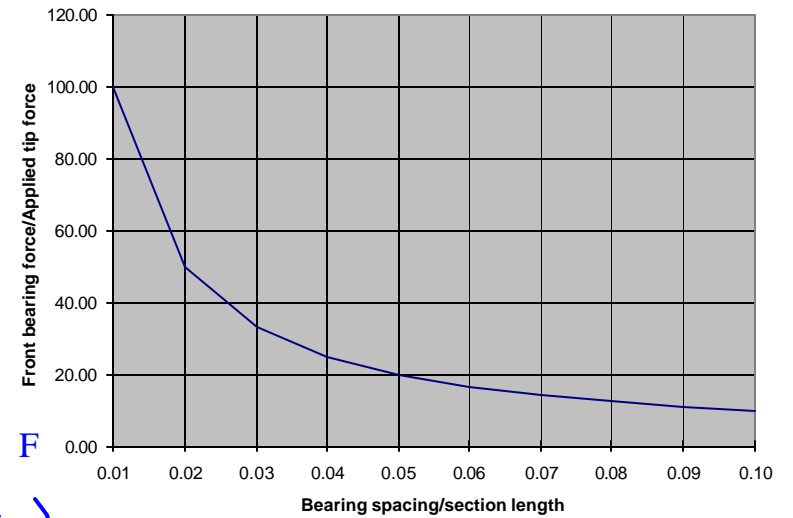
- Simple linkages often cannot meet FRs for large motion or extreme force
 - A linear actuator cannot be effectively (huge stroke or huge forces are required) attached to a point on a 4-bar linkage to allow the output link to move through 180 degree motion

E.g., excavator bucket, concrete pump booms....use a **6-bar** linkage

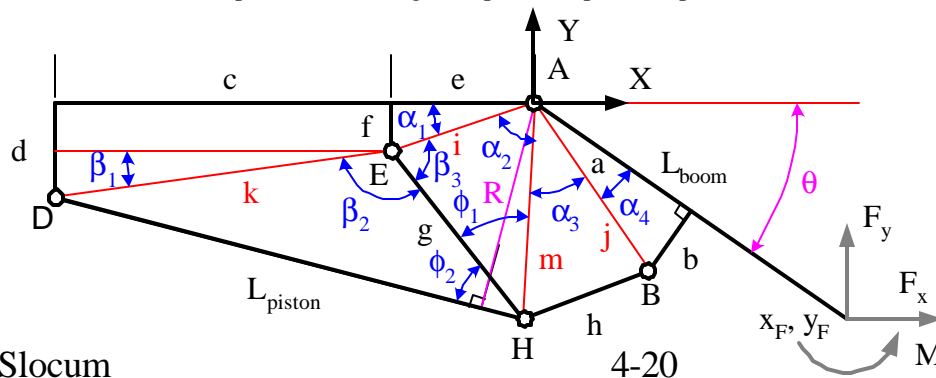


Extending Linkages

- Many extending systems have the following FRs
 - Compact for transport
 - Rapid set-up
 - Long reach capability during use



<http://www.schwing.com/products/pdf/39X.pdf>



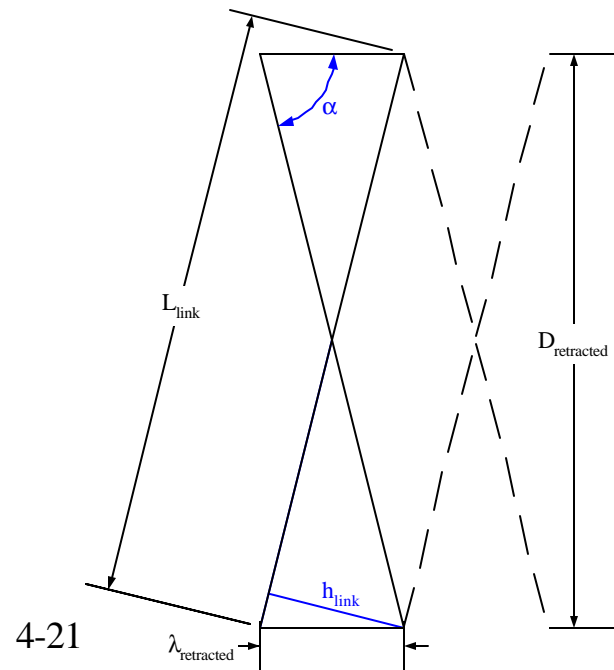
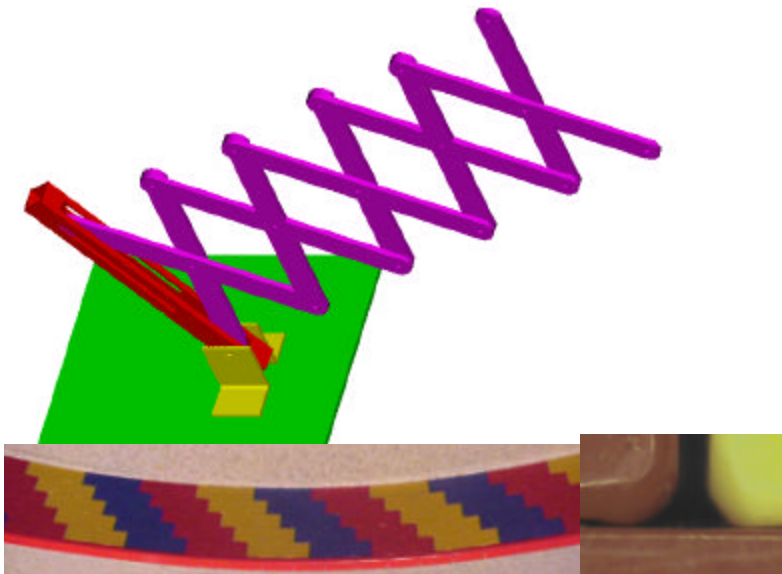
<http://www.terexlift.com/catalog/catopdfs/rt300ser.pdf>

Extending Linkages: *Scissor Linkages*

- Scissor Linkages (*Lazy Tongs*) are a great way to get a **LARGE** range of motion in a small package (that's Big John next to the tongs)



- How does one develop a system as simple in principle, but as complex in detail as the Lazy Tongs?
 - The devil is in the details



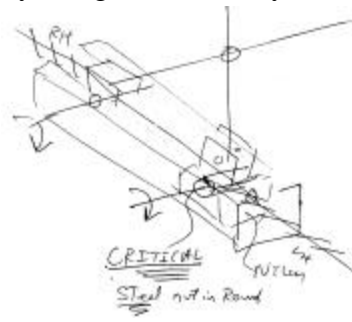
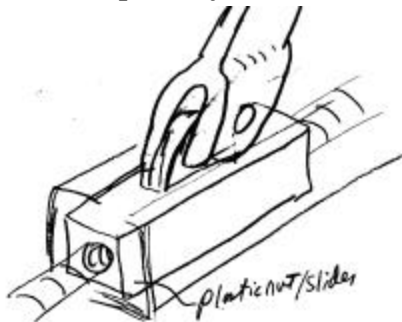
Extending Linkages: *Scissor Linkage Example*

FRDPARRC Sheet Topic: Long Reach System

Functional Requirement (Event) Long reach system to rapidly zoom over to opponent and jam their machine and pendulum, and also prevent them from moving around on the table (create a baby gate!)

Design Parameter (description of idea) Scissor linkage (Lazy Tongs) actuated by one base link pin fixed and the other sliding using a pin-in-slot joint

Sketch:



Analysis (physics in words) The input force will act over a short distance, and the output over a long distance, so it will be much less. However, to resist collapsing by opponent pushing against us will be easier since friction in the pins now will work against opponent. Use lazy_tongs.xls to determine feasibility and optimize.

Analysis

See spreadsheet output. To first order, we have a 7.5:1 ratio, so if we generate 300 N of force with a screw to compress the ends, with 50% efficiency we can get 20N of force to jam our opponent and their pendulum.

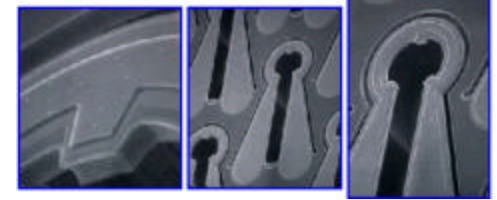
References: Topic 4 notes and lazy_tongs spreadsheet and *Niagara Balls* contest

Risks: Not enough force, opponent will deflect or push us away.

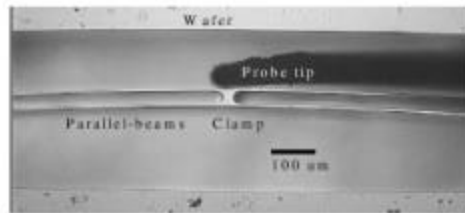
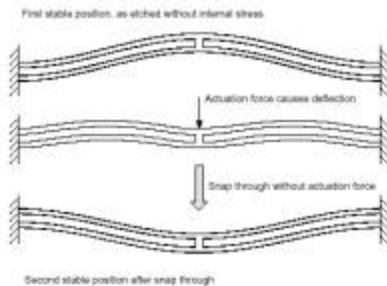
Countermeasures: shoot high and passive on-way gripper captures beam, and then slide down their beam; thus we form a tether to their pendulum to gumfoozilate them.



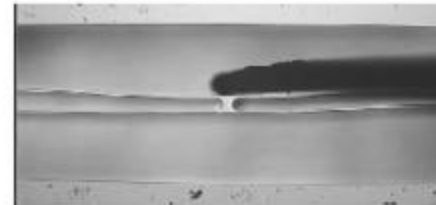
Compliant Mechanisms



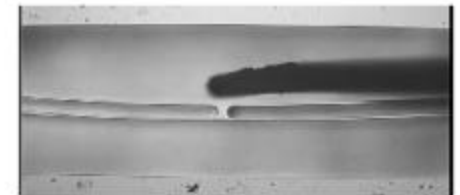
- The pin joints in linkages are often the major source of error motions
- When only small motions are required, the pin joints can be replaced with flexural elements, thus forming a *compliant mechanism*
 - This has been used for decades as a means to create extremely high accuracy small range of motion instrument stages
 - Many *Micro Electro Mechanical Systems* (MEMS) use tiny silicon flexures



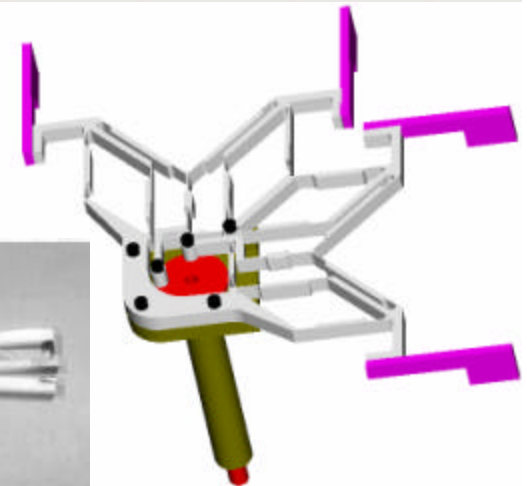
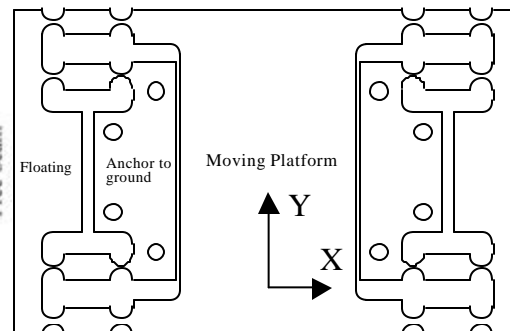
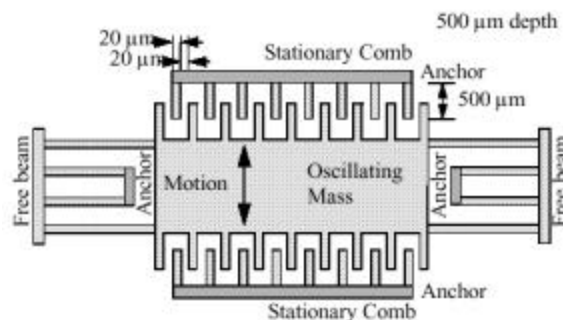
(a) The mechanism as etched; the probe is ready to push



(b) Deflection as the probe pushes the mechanism.



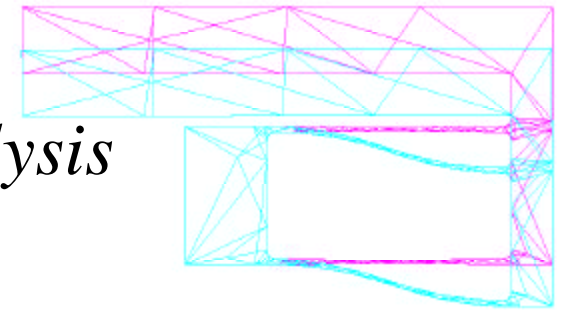
(c) The mechanism snaps to its second stable position after being



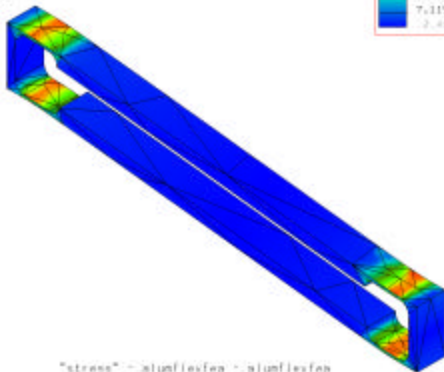
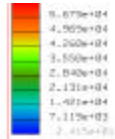
Compliant Mechanisms: *Analysis*



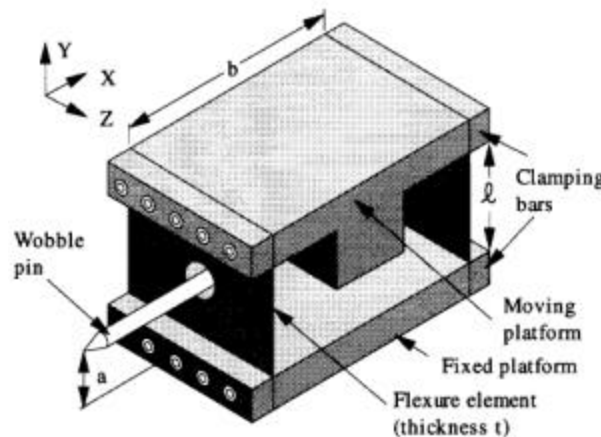
- Finite Element Analysis is a powerful design tool
 - Design Parameters (dimensions) are changed until desired performance (stress, deflection) are obtained
- This 4-bar compliant mechanisms was designed to be made from titanium for strength, weight, and temperature resistance
 - It was machined by an OMAX abrasive jet machining center for a cost of \$200 (vs. \$1000 to wire EDM)
 - When installed, it was strong enough to resist damage by the controls engineers!



Stress von Mises (Maximum)
 Avg. Max +6.0881E+03
 Avg. Min +2.4153E+03
 Deformed Original Model
 Max Disp +5.4848E-03
 Scale 1.8488E+03
 Load: load1



"stress" = aludeflex - aludeflex

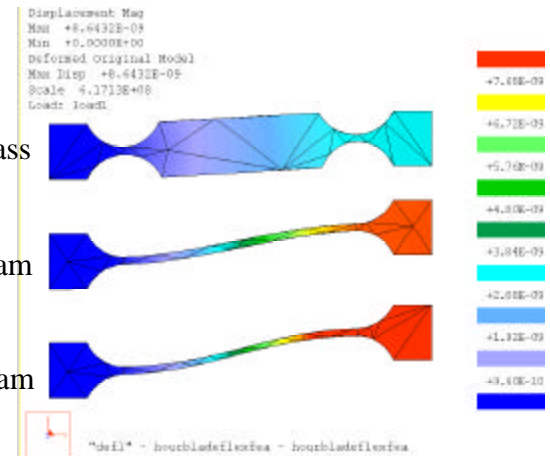


4-24

Hourglass

Straight beam

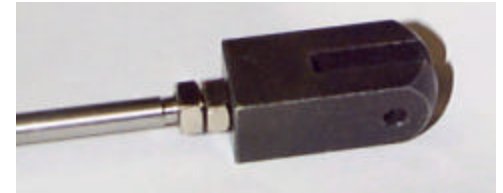
Tapered beam

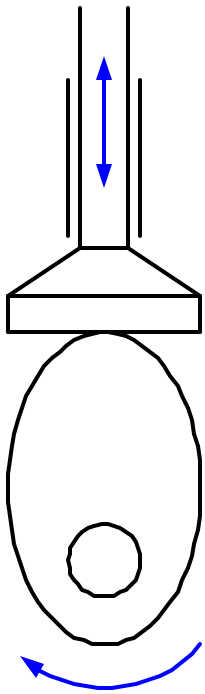


2/6/2002

Manufacturing & Robust Design

- Most machining processes can be used (milling, abrasive waterjet, wire EDM)
- Abrasive waterjet machining allows for very complex compliant mechanisms to be machined very rapidly
 - Example: A *wiffle tree* evenly spreads out a point load
 - Windshield wipers are the most common example
 - This wiffle tree was cut on an OMAX machine in only a couple hours
 - NOTE the use of a large blade flexure to support the right side of the OMAX machine's X axis, to allow for thermal growth
 - » This is a machine-tool-precision very-small-range-of-motion 4-bar linkage



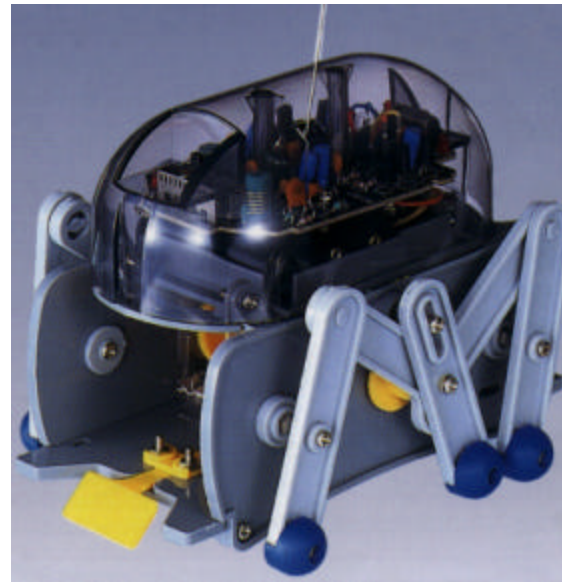
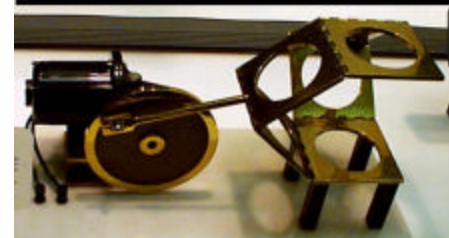
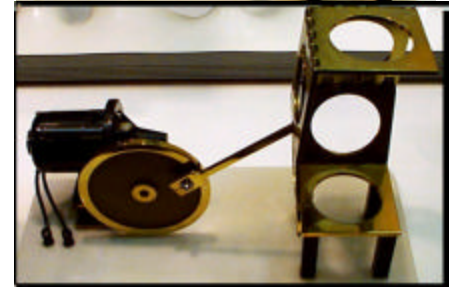


Mechanism Mania!

- Primitive walking can be achieved with relatively simple linkages
 - The act of walking is either a controlled fall, or moving constraints and then shifting the CG
 - Walkers are impressive, but are difficult to make into an effective strategy
- Spatial mechanisms are also very impressive and can be quite useful, although difficult to design



www.legomindstorms.com/darkside



Linus Park created an awesome walker for 2.007 2000 MechaImpactAgeddon!