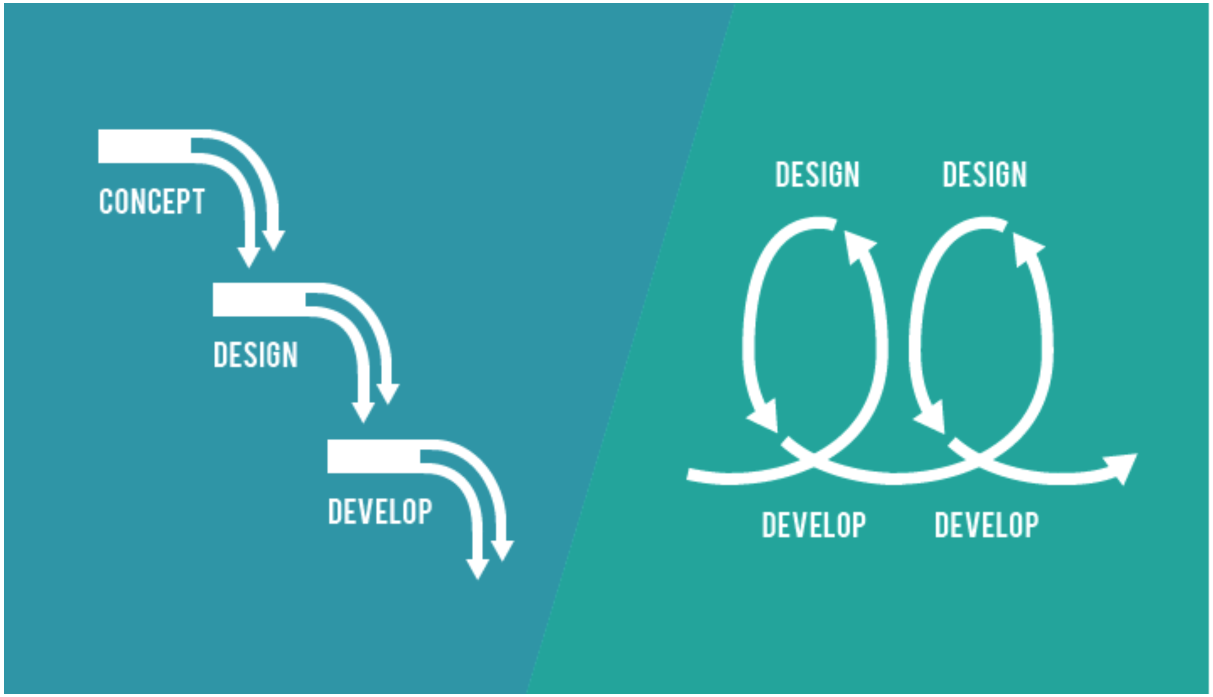
# ROCO222: Intro to sensors and actuators

Lecture 6

Principles of mechanical design

# Agile design

Agile process
- Emphasize production of on-time and on-budget deliverables
- Don’t aim at immediate perfection
- Products can always be tweaked down the road
- Can be done with iterations, short, intense periods of production
- Using smaller, more achievable goals
- Use further iterations down the road



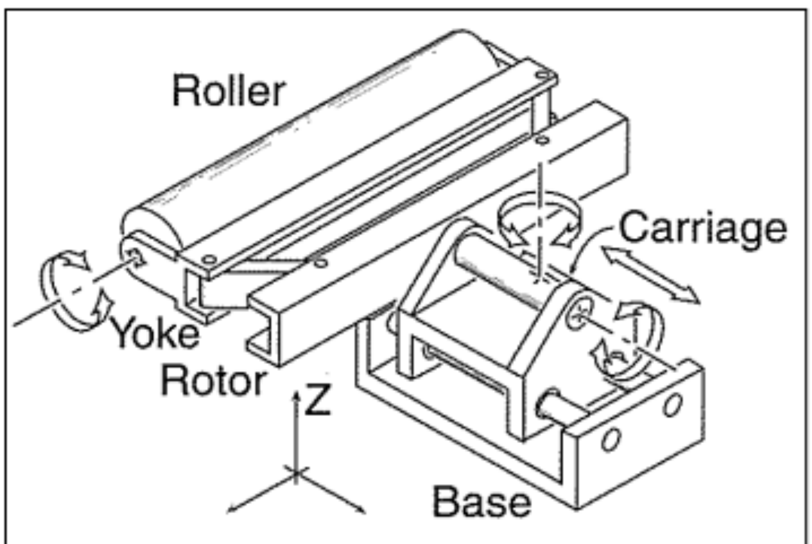

**Waterfall** **Agile**

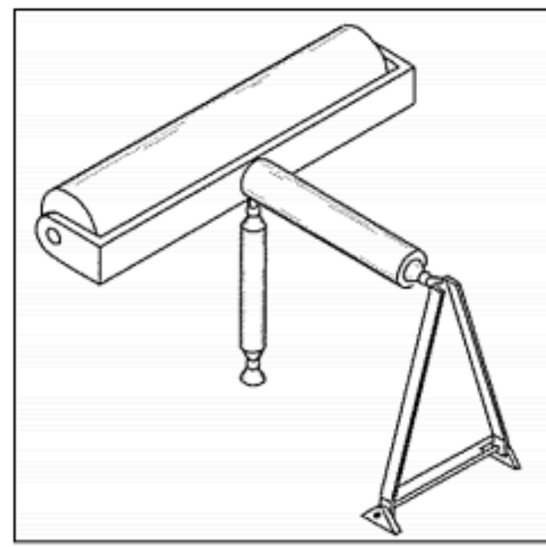
# Occam's razor

- Keep things simple to start and add detail as the design develops.
- Minimize the number of components

# Simplicity versus complexity

- Create designs that are explicitly simple
- Keep complexity intrinsic
- The less thought and less knowledge a device requires for production, testing, and use, the simpler it is



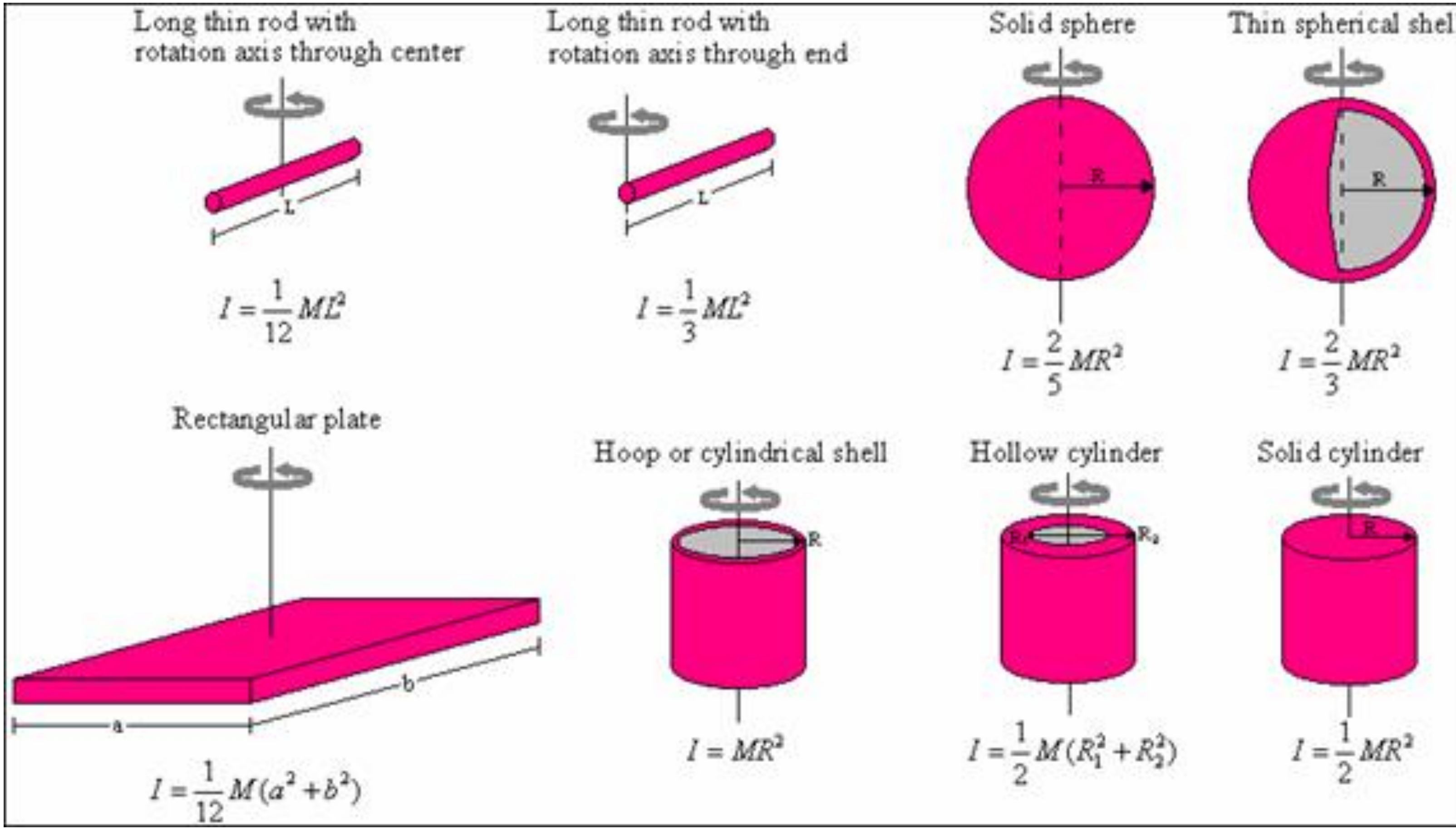
# Simplicity versus complexity

- Simple design means user sees nothing that looks complicated
- Complexity may be present but hidden to the designer
- Whenever possible use off-the-shelf components.
- Use pre-made complex parts from another source
- E,g, buy a box (“electronics enclosure”) instead of making one.
- Set approach: bolt simple parts together to create more complex structures.

# Don't try to defy the laws of nature

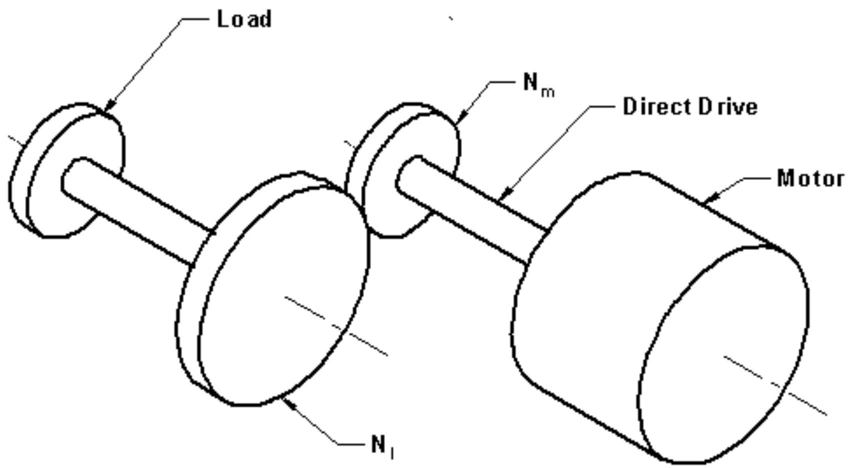

- To do a good design you need to:
- Understand the basic physics
- Newton's Laws
- Laws of Thermodynamics
- Ampere's Law, Faraday's Law, Lenz's Law

# Moment of inertia




- To keep I down we must keep mass close to axis of rotation
- Moment of inertia scales with distance from axis squared

# Effect of gear ratios on MoI




$$\tau_{out} = \frac{1}{\eta}\tau_{in}$$

$$\theta_{out} = \eta\theta_{in}$$

- In geared systems the inertia of the load can be dominated by the inertia of the rotor

Total Inertia realized at load is given by

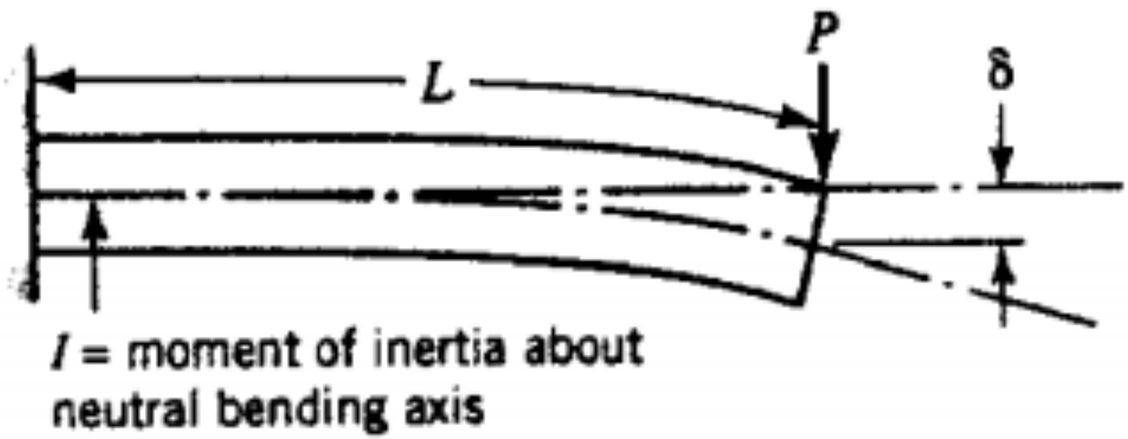
$$J_{total} = J_{load} + N^2 \,.\, J_{motor}$$

- Therefore we cannot always use a very large mechanical advantage

# Beam deflection scales with $L^3$

Cantilever beam loaded at end

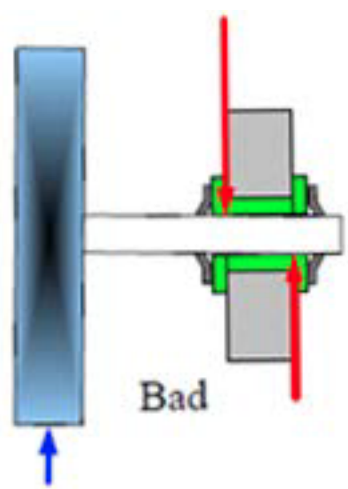
$$\delta = \frac{PL^3}{3EI}$$

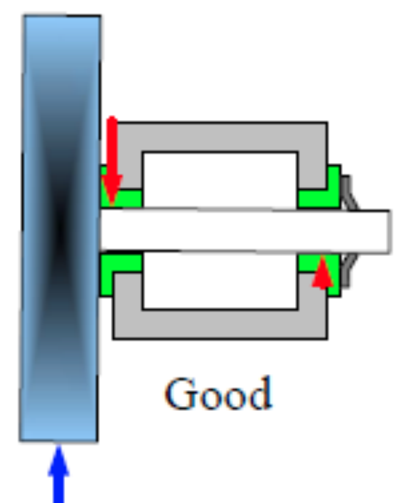



- Therefore to maintain harm length should be as short as possible

# Saint-Venant's principle

- The difference between the effects of two different but statically equivalent loads becomes very small at sufficiently large distances from load
- If an effect is to dominate a system, it must be applied over 3-5 characteristic dimensions of the system
- Mounting bearings to support a shaft, bearings should be spaced at least 3-5 shaft diameters apart if bearings are to effectively resist moments applied to the shaft

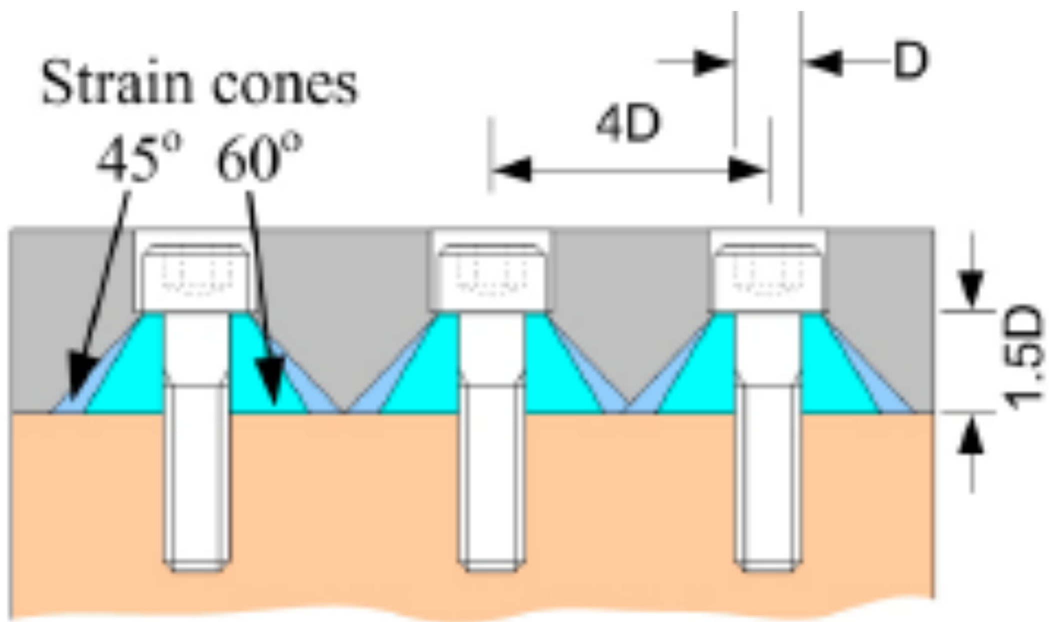


# Saint-Venant's principle

- When bolting components together, in order to make the bolted joint act almost as it were welded together the bolts' strain (stress) cones should overlap

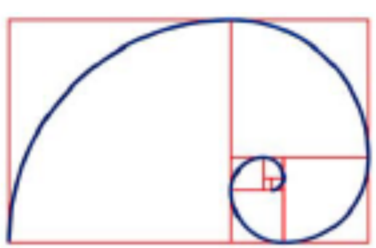
- The strain cone emanates from 45° to 60° under the bolt head. The strain cones typically overlap if the bolts are spaced less than 3-5 bolt diameters apart

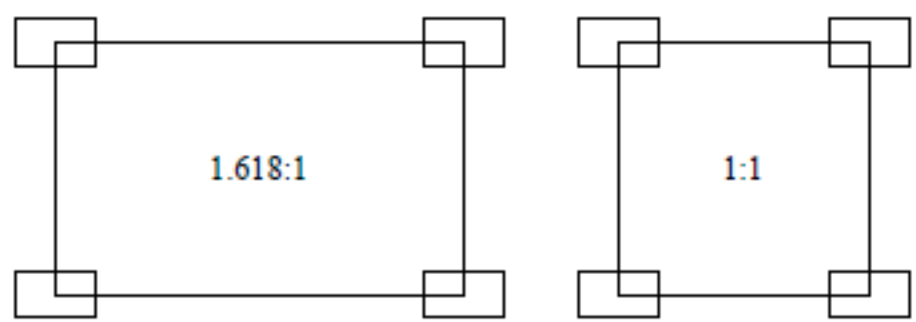


# Golden rectangle

- The Golden Rectangle, discovered by Pythagoras, is a rectangle whose sides are in proportion such that when a square is cut from the rectangle, the remaining rectangle has the same proportions as the original rectangle, i.e., a/b = 1.618

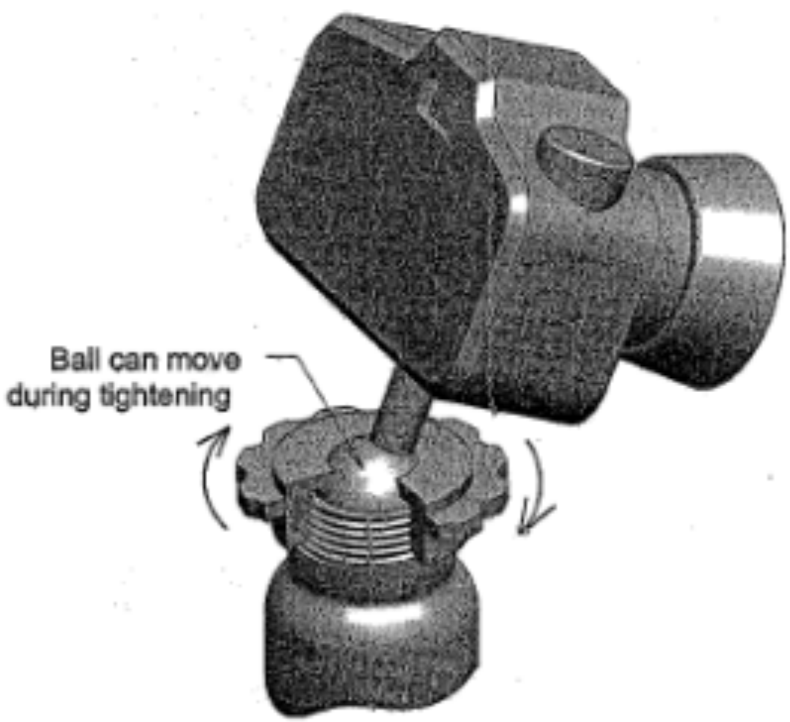
- Don’t know what size it should be?
- Start with a ratio of about 1.6:1



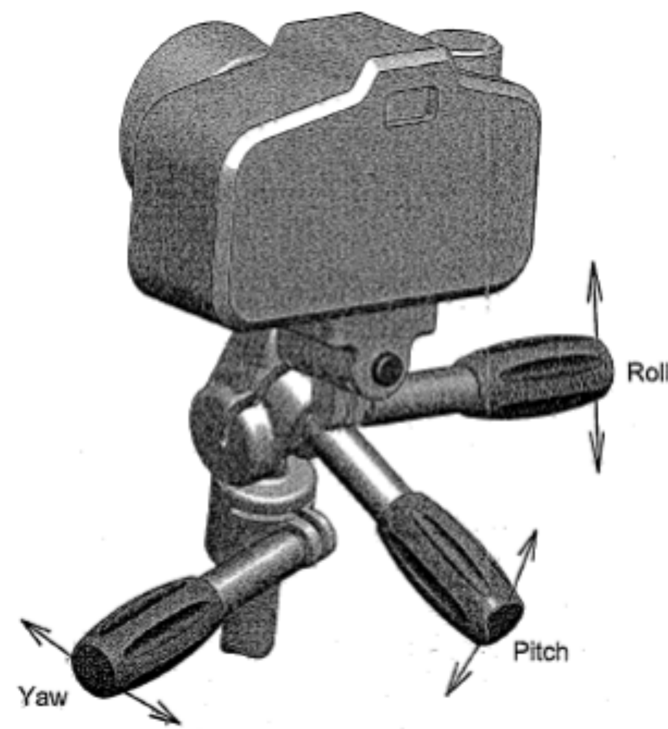


# Independence of function

- Keep the functions of a design independent from one another




Not independent



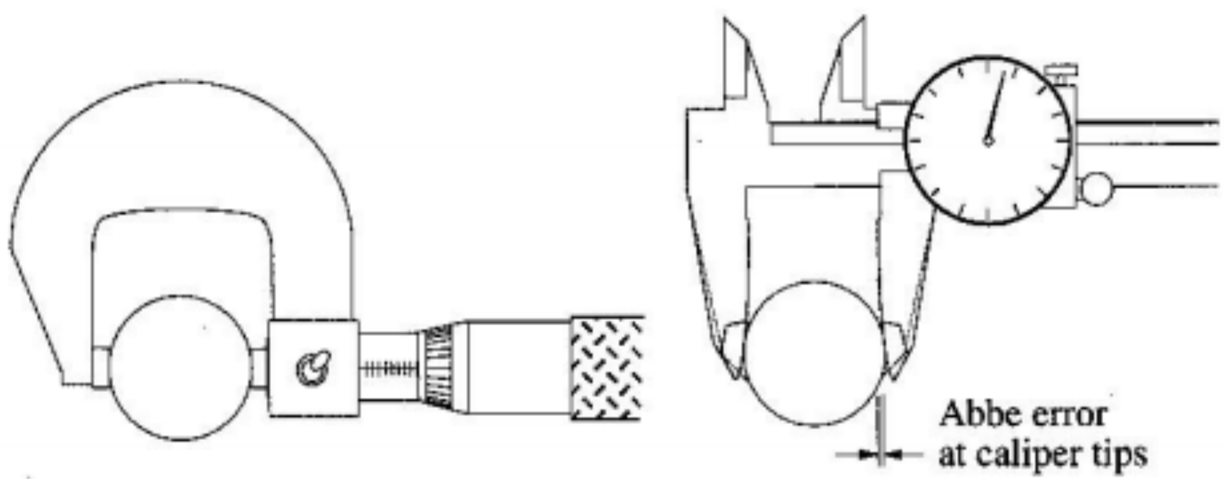

independent

# Abbe's principle

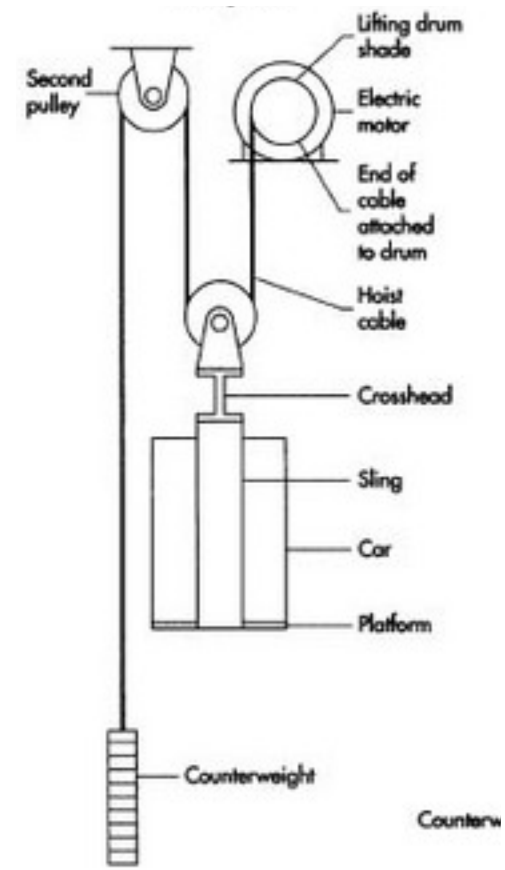
- Small angular deflections are amplified by distance to create large linear displacements

- Always try to place the measurement system as close to the line of action (the process) as possible

- Always try to place bearings and actuators as close to the line of action (the process) as possible



# Self-principles



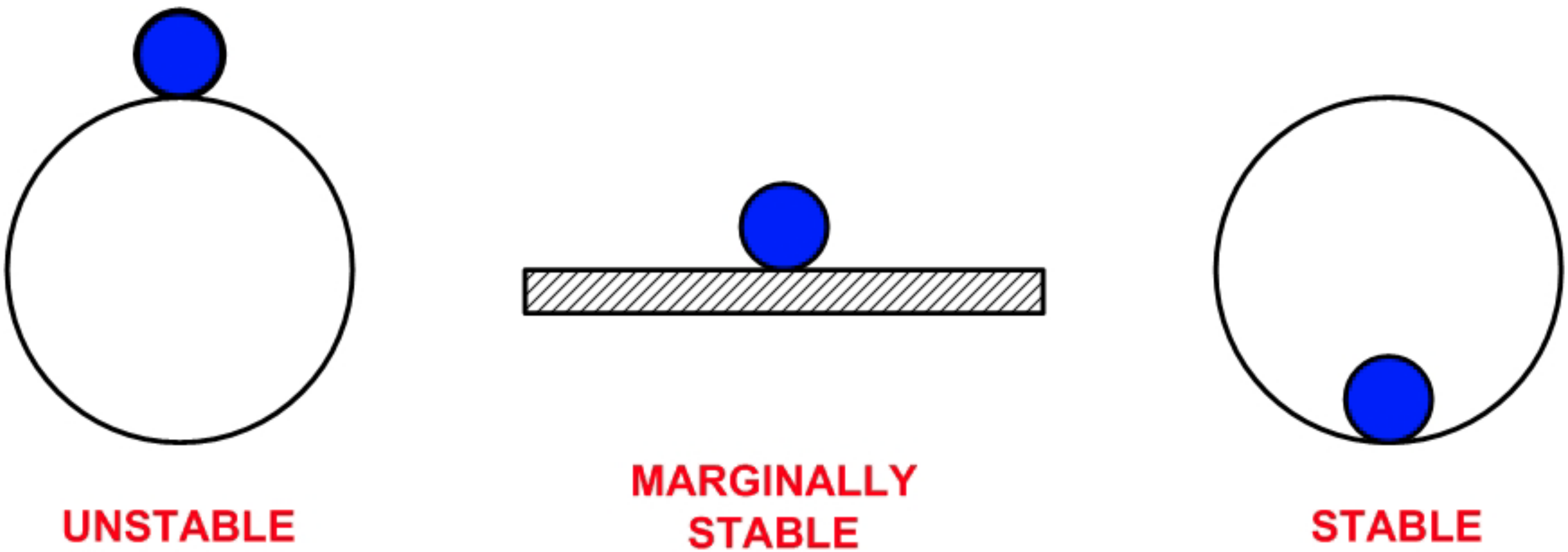

- Use an object’s geometry or other property to prevent a problem

- Self-help that balances forces - e.g. counterweights on cable-operated elevators

- Self-help that redirects forces - e.g. hand action when using scissors naturally forces the blades’ cutting edges together

# Stability

- Stable, neutrally stable, and unstable effects can help or hurt
- Some things can be made neutrally stable and fast
- Vibration can induce instability
- Beware of buckling of compression members



# Symmetry

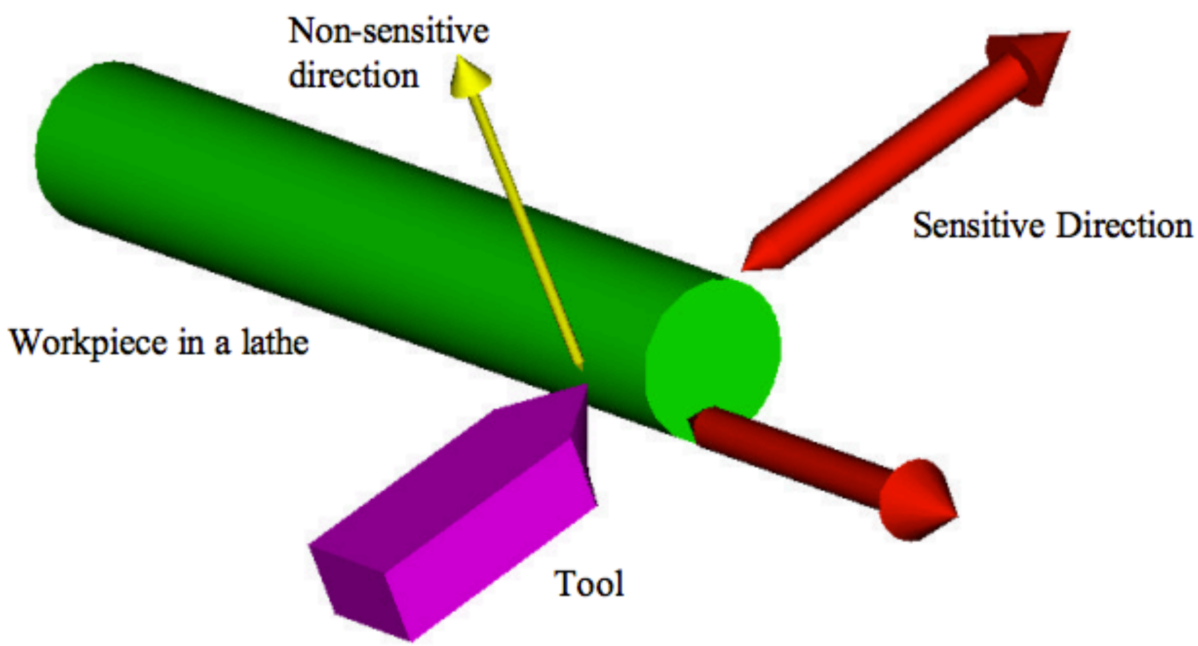
- In general, symmetry a good thing in a system
- Good starting point in a design
- Try a design that is symmetric
- Then impose reciprocity to consider a design that is not symmetric

# Accuracy, repeatability, resolution

- First make your machine repeatable
- Then if you have fine enough resolution, tune for accuracy
- Designing a machine that has good accuracy, repeatability, and resolution is not a black art
- It ***appears*** to be a black art only when the observer lacks the time or resources to use scientific principles to discover the true nature of the phenomena.

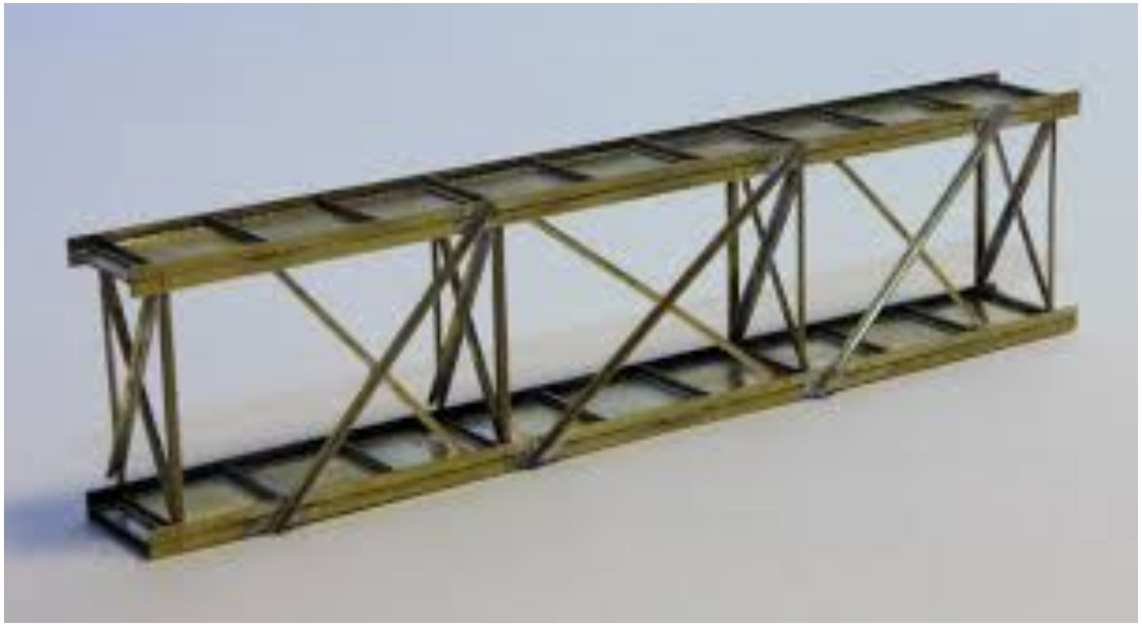
# Sensitive directions

- Identify the directions in which accuracy and repeatability are most important
- Put a lot of effort into accuracy for the directions in which you need it
- Don’t pay for performance in a direction that is not needed
- This is also how the human motor system operates!



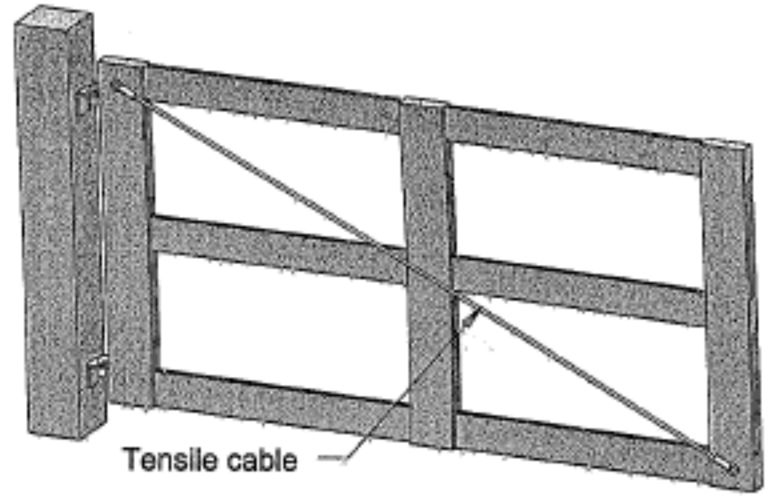
# Parallel axis theorem

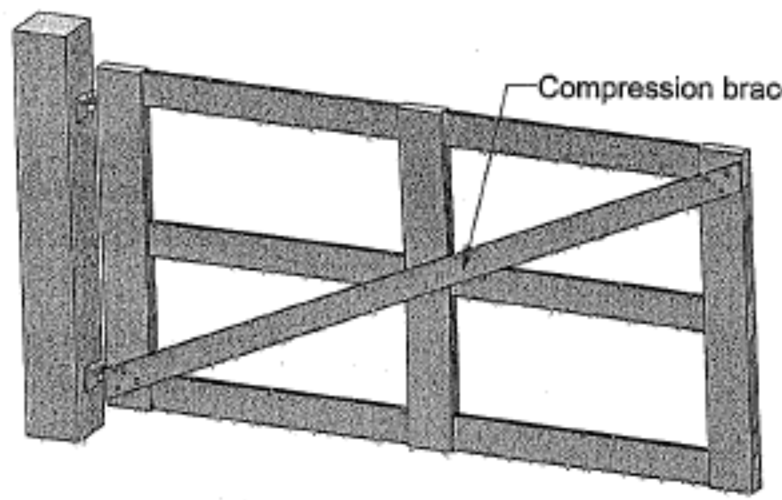
- The Parallel Axis Theorem useful for calculating the moments of inertia for complex objects
- The Parallel Axis Theorem even more useful for as a philosophy for design
- That is, the stiffness of an design goes with the square of the distance of the structural members from the neutral axis



# Triangulate for stiffness

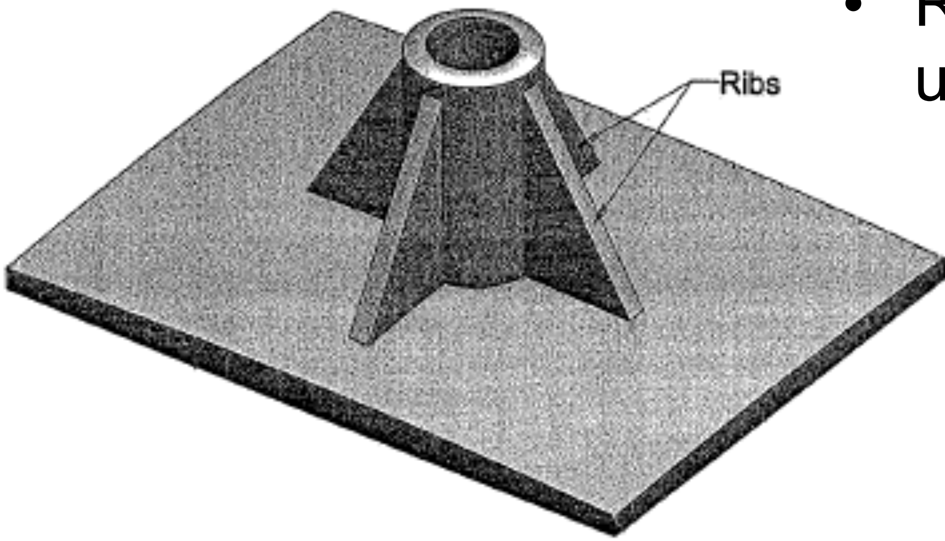
- Triangulate parts and structures to make them stiffer
- Triangulation applies to structures and structural elements
- When components or structures need to be stiff, create triangles



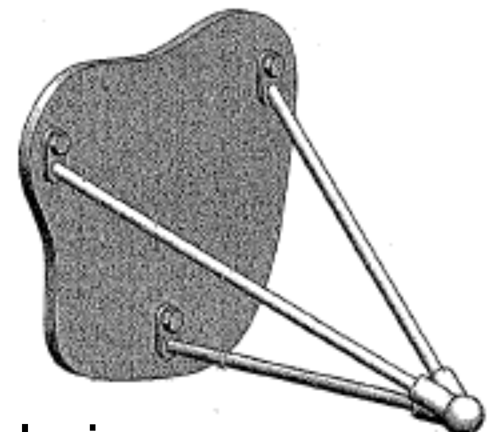




- Triangulating members typically have tension and compression loads rather than bending loads

# Triangulate for stiffness



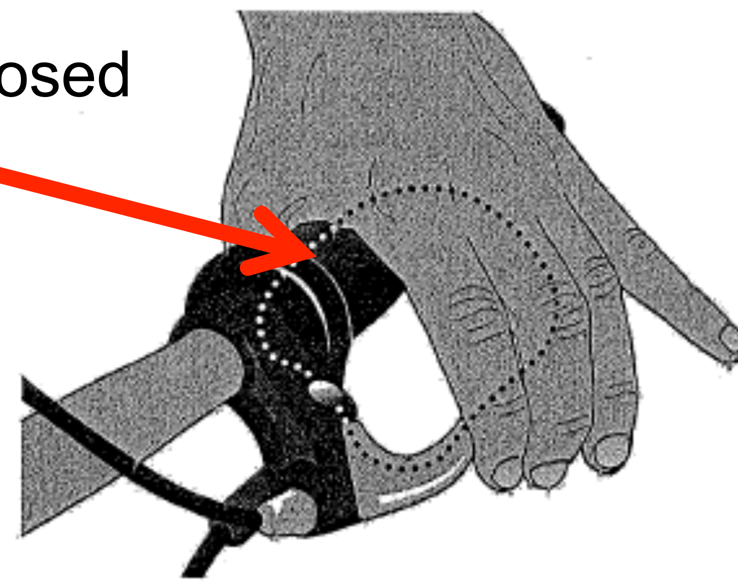

- Ribs stiffen the structure by using thin braces



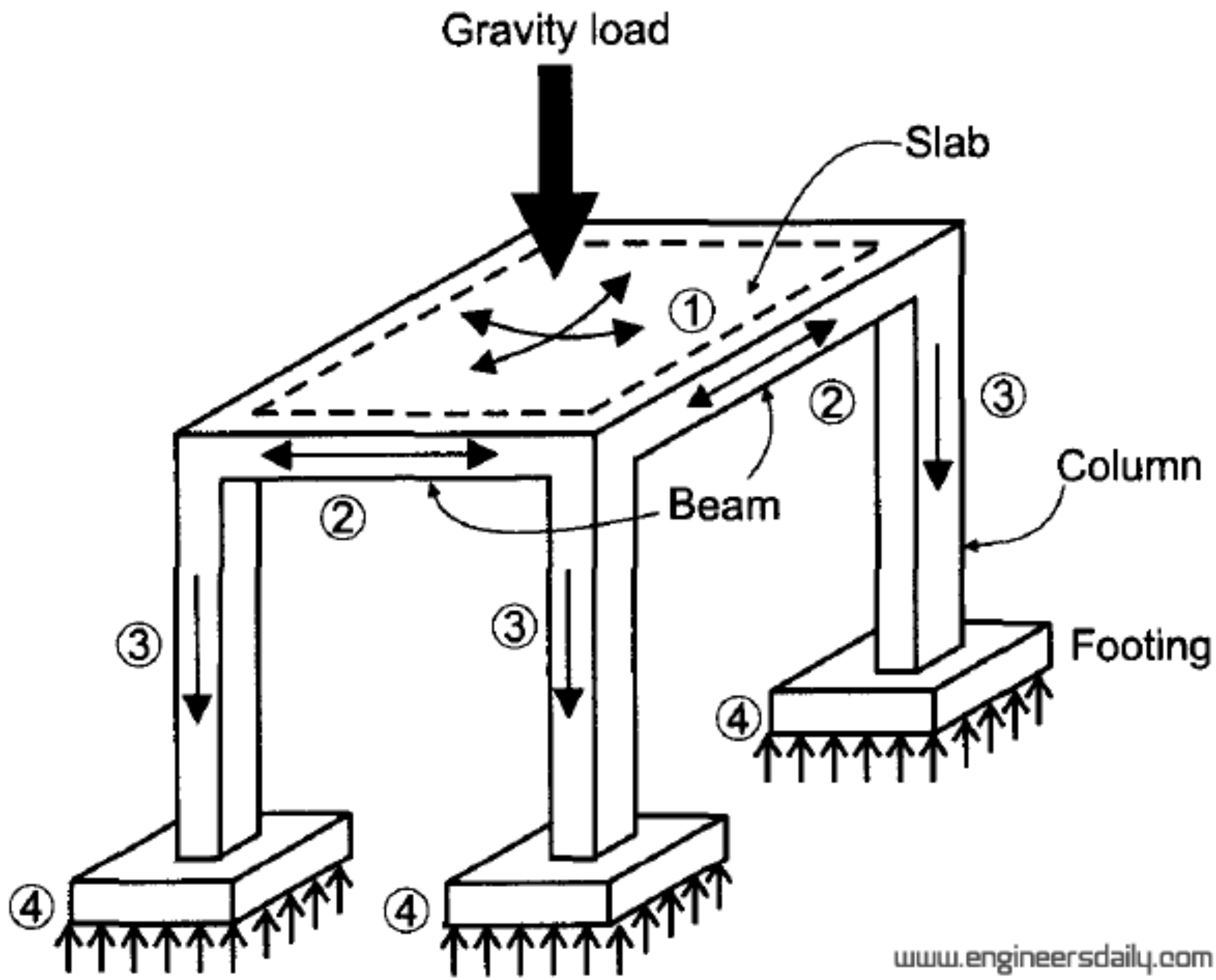
- The three-dimensional equivalent of a triangle is a tetrahedron
- Four triangles give three-dimensional rigidity
- NB: stiffer does not always mean stronger or more robust!
- Stiffening transfers loads to a different place, a place that might be weaker or more susceptible to failure!

# Load paths

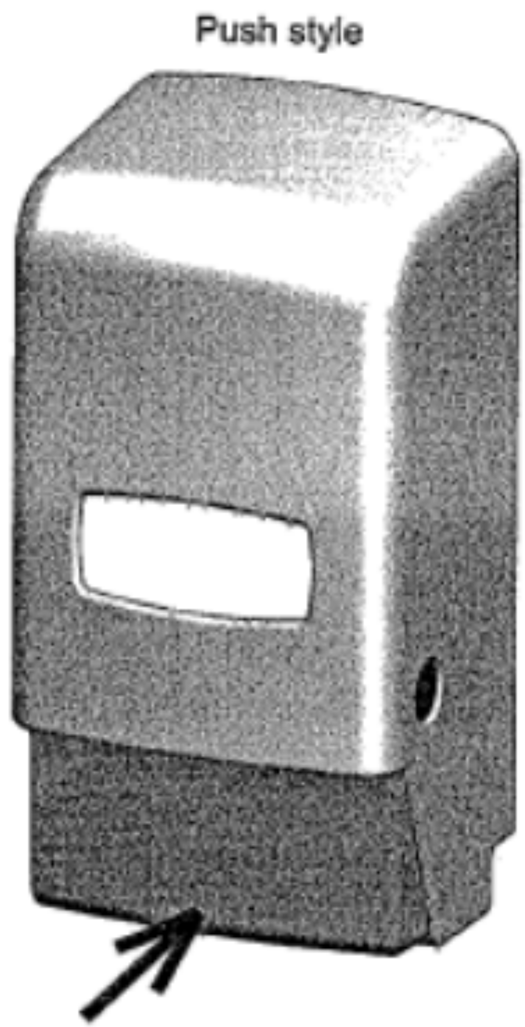
- Plan the load paths in parts, structures, and assemblies.
- You want the load path to be:
- Short, direct, non-redundant, or, barring that, elastic
- Subtle differences can have a huge effect on the performance of a machine
- E.g. a bicycle handbrake is squeezed rather than pulled or pushed
- The load path is thereby locally closed



# Load paths through a building



# Load paths in wall-mounted soap dispensers

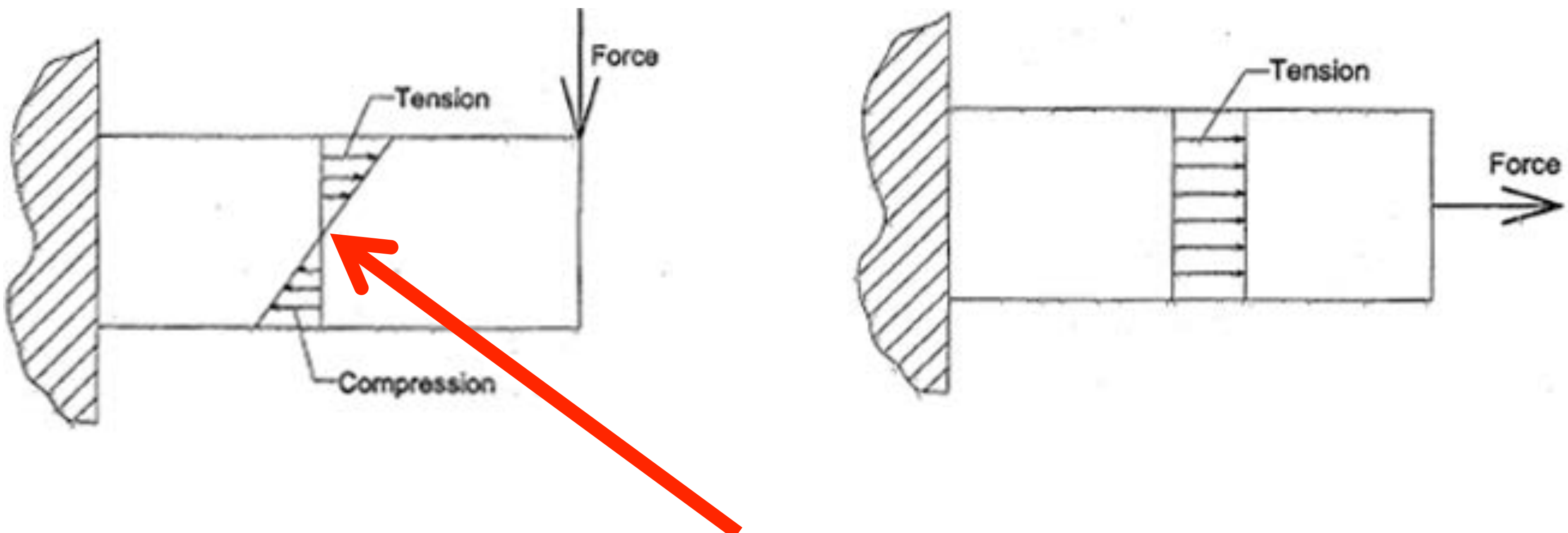




Bad
Load path complex

Good
Transfers load more directly

# Avoid bending stresses

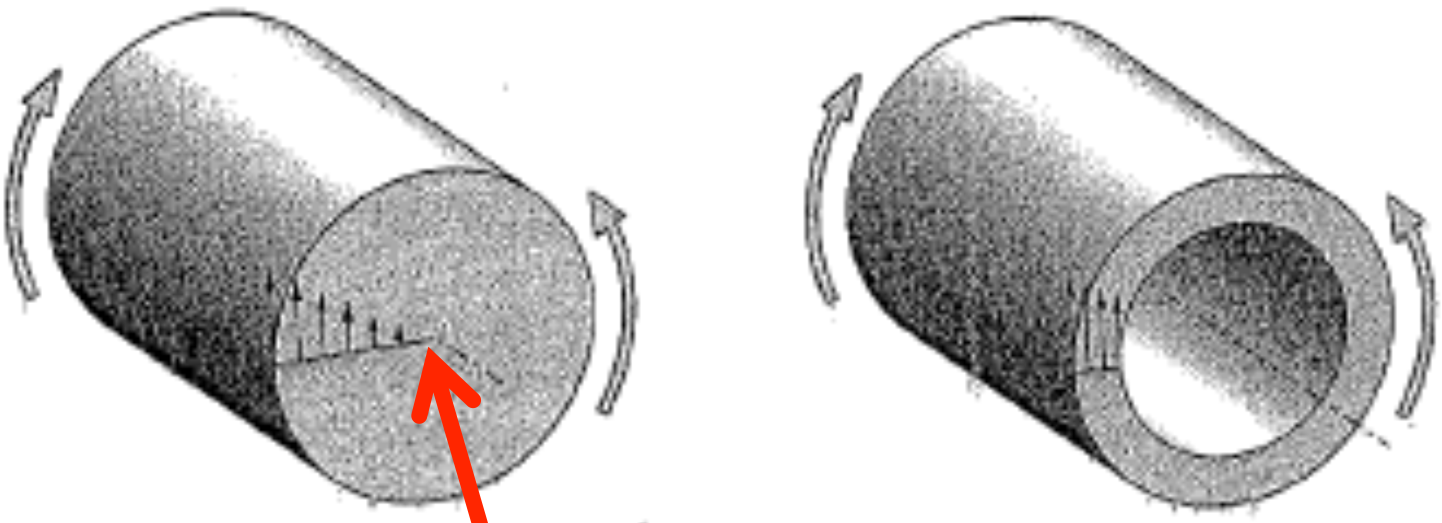
- Favor tension and compression over bending
- Triangulating members typically have tension and compression loads rather than bending loads




- Here lots of material is unstressed and contributes nothing to rigidity or strength

# Avoid bending stresses

- Design to get uniform stress

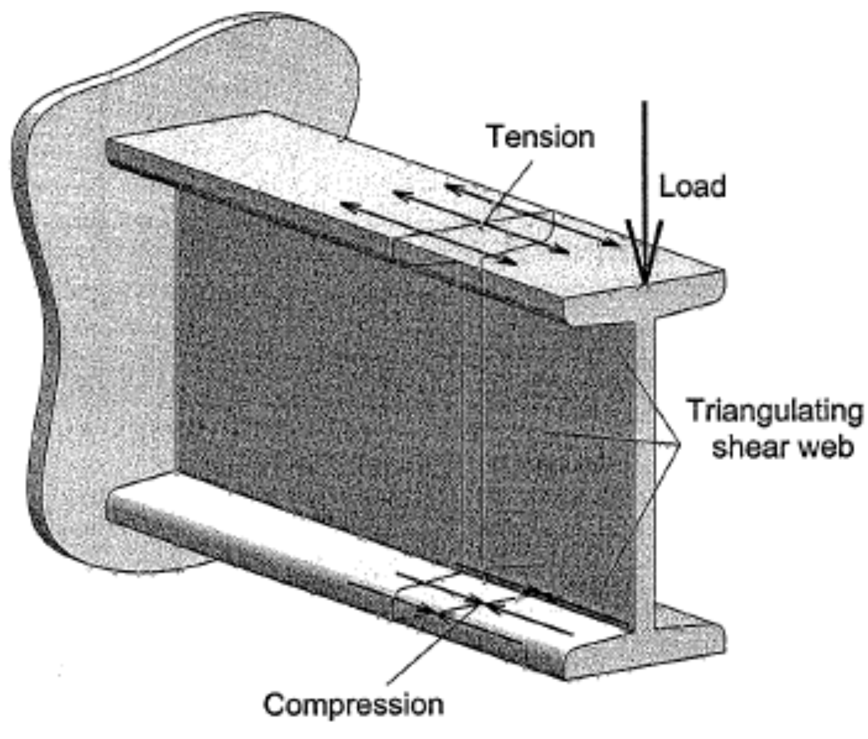


- Shear stress distributions in solid and hollow torsion shafts are shown above
- Material near the center of a solid shaft carries no load

  - Material in a thin, hollow shaft has nearly constant shear
  - In bending and torsion, much of the middle material contributes nothing to carrying load

# Avoid bending stresses

- I-section beams are a practical way to use material efficiently to support bending deflections.
- Most of the material is at the maximum possible distance from the centroid. Thus, the material in an I-beam is
  - Nearly uniformly loaded
  - St the maximum stress



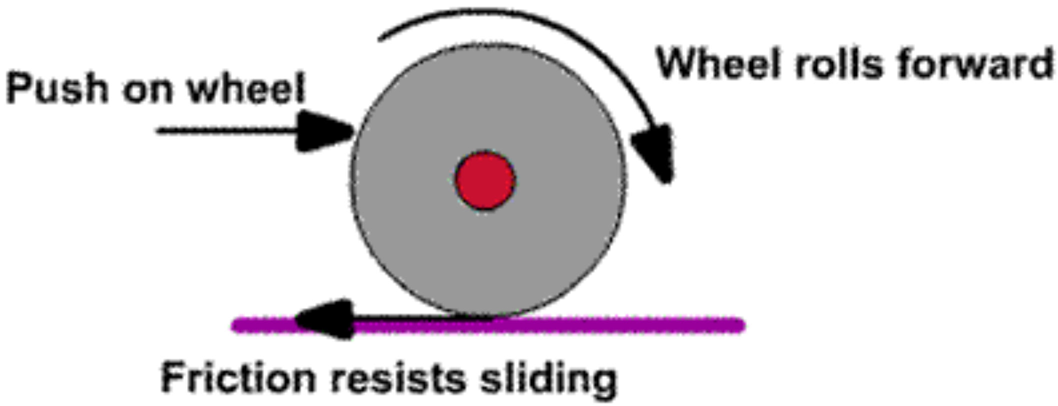
# Avoid bending stresses: Robotics example

- Single side only loading is bad
- It puts torque on shaft

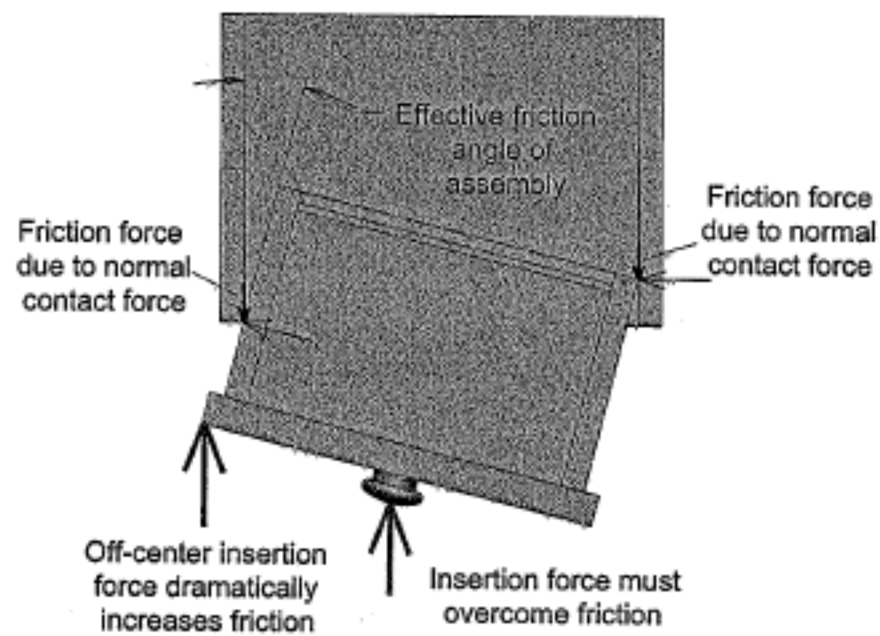
- This design is much better as both end supported
- avoiding torque on shaft

# Manage friction

- Avoid sliding friction if possible
- Use rolling element bearings




- Maximize the length of linearly-guided components
- Linearly-guided components jam when the insertion force is inadequate to overcome the friction of the guides' contacts

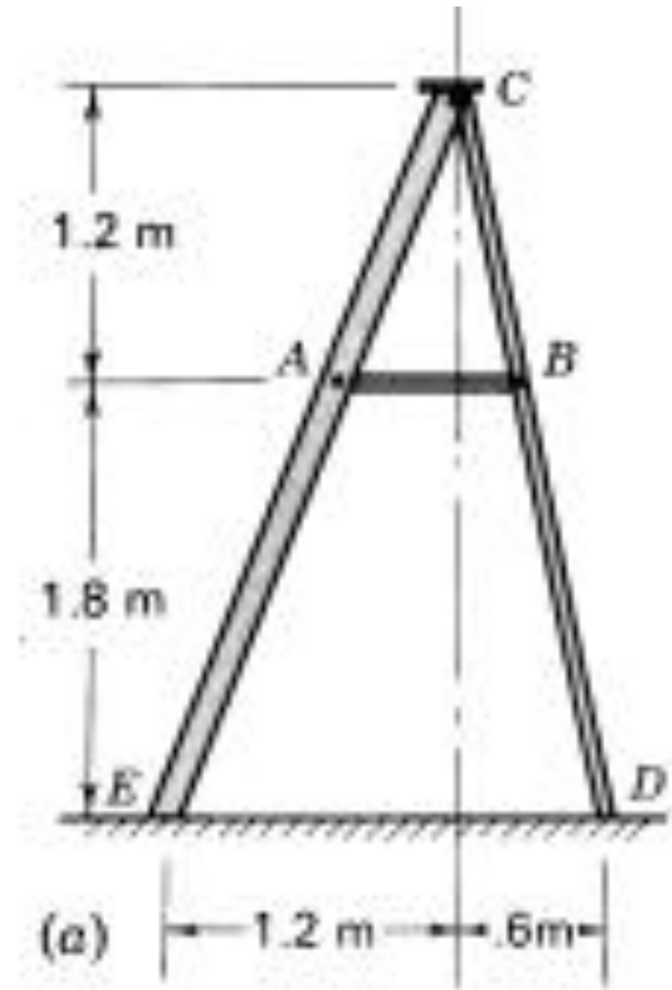


# Free body diagrams

To analyze a complex object:

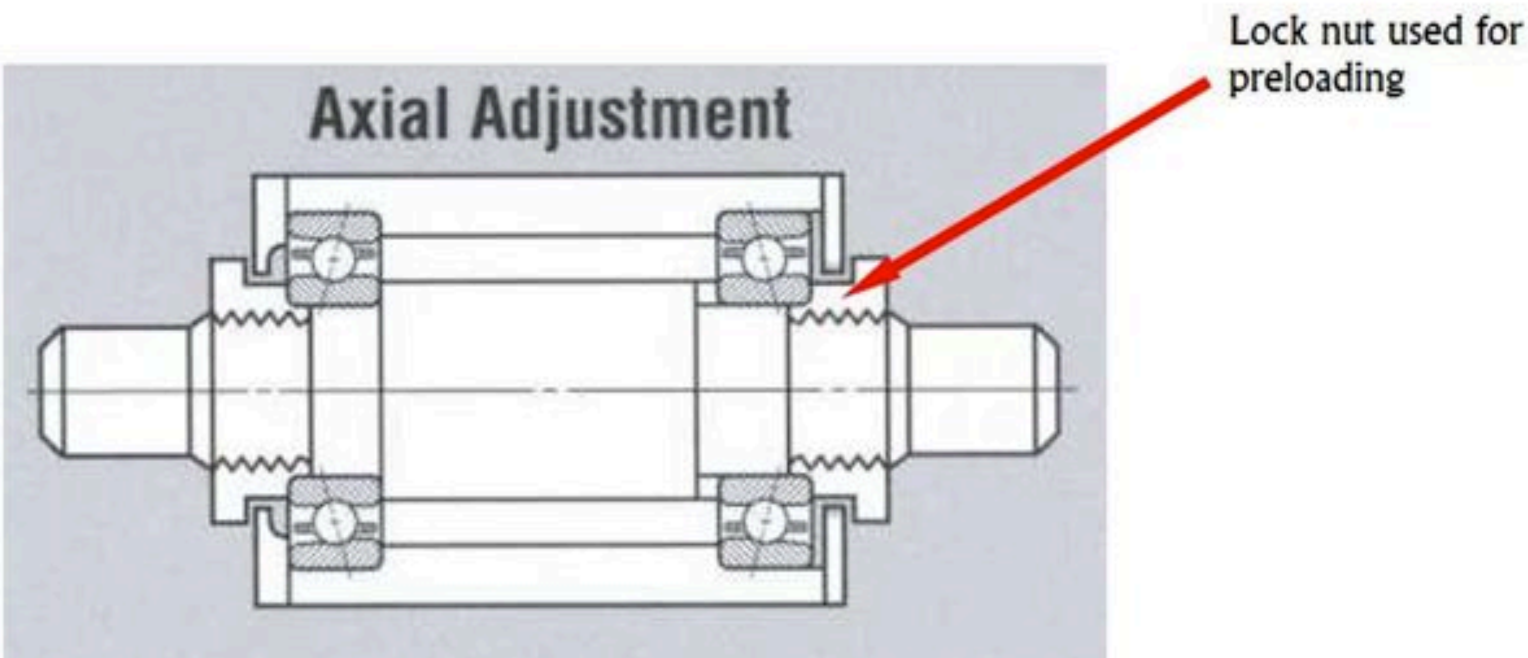
- Separate it into parts
- Label the forces and moments on each part that are imposed by other parts

- Free body diagrams allow a designer to show components and their relationship to each other with respect to forces transmitted between them



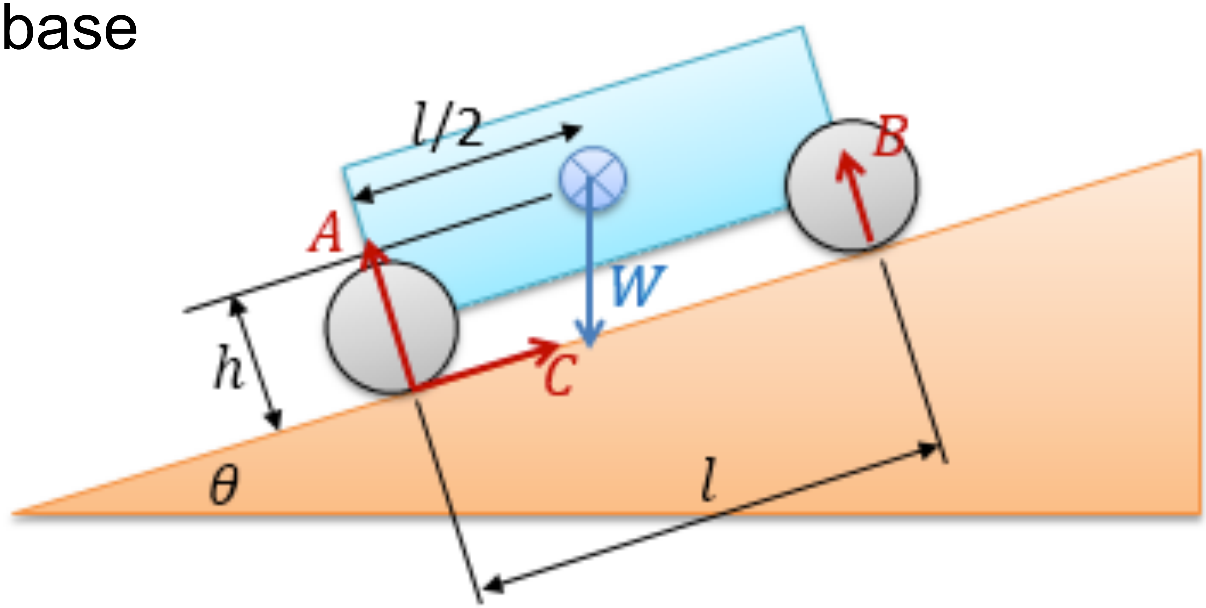
# Preload

- Loose fits between objects mean you cannot predict where one object will be with respect to the other
- Apply loads between the objects as part of manufacturing and assembly to take out the slack in the system.
- E.g. use preloaded bearings



# Centers of action

- The Centers of Action are points at which when a force is applied, no moments are created
- Center of Mass, Center of gravity, center of Stiffness, center of Friction
- A system is most robust when forces are applied as near as possible to the Centers of Action
- When a vehicle drives up an incline, it will not tip over if the downward projection of the CoG remains within the wheelbase



# Exact constraint design

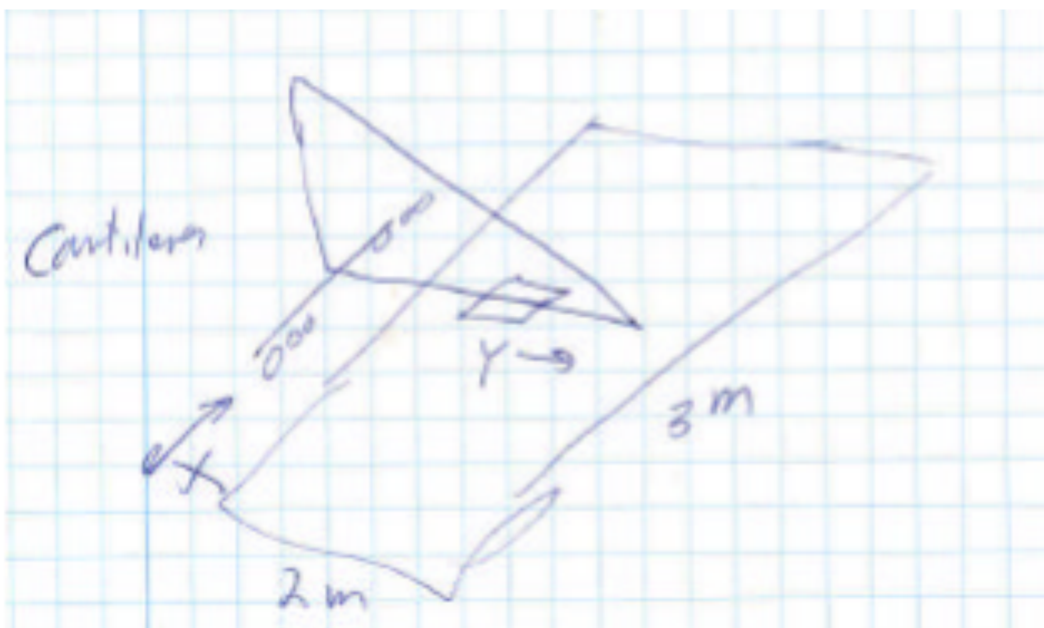
- The number of points at which a body is held or supported should be equal to the number of degrees of freedom that are to be constrained
- Don’t over constrain a design!

4 legs on the ground may lead to may lead to a wobbly table

Three legs are always stable

# Stick figures

- Initially sketch an idea using simple stick figures, which also denote where major coordinate systems are located in the design
- The coordinate systems are to be used for modeling individual modules:
- E.g., for creating an error budget to predict a machine's repeatability and accuracy



# Tips to gain good design principles

- You need to get develop an intuition for good design
- Comes with practical design experience
- Learn for examining other good mechanism designs
- Play around and dismantle and reconstruct good designs
- Practice makes perfect!

# ROCO222: Intro to sensors and actuators

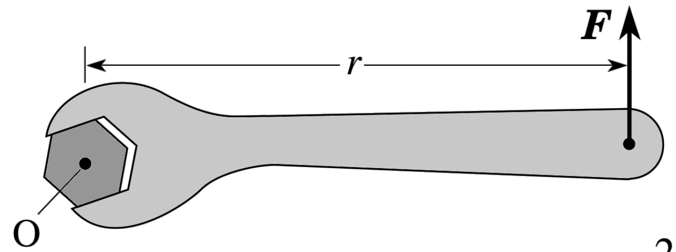
Lecture 6

Mechanical advantage

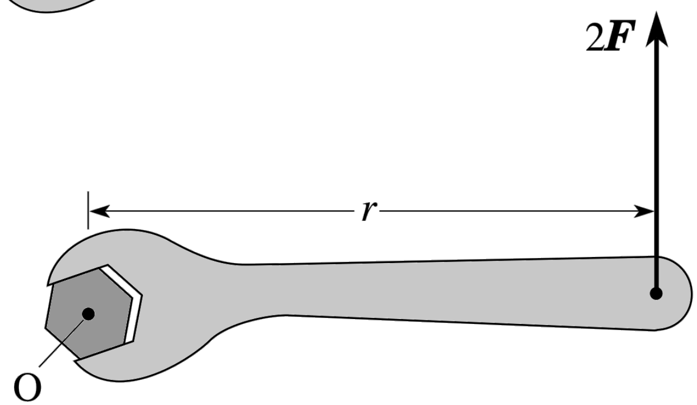
# Torque

- Torque = Force applied x lever arm
- Where lever arm is the perpendicular distance

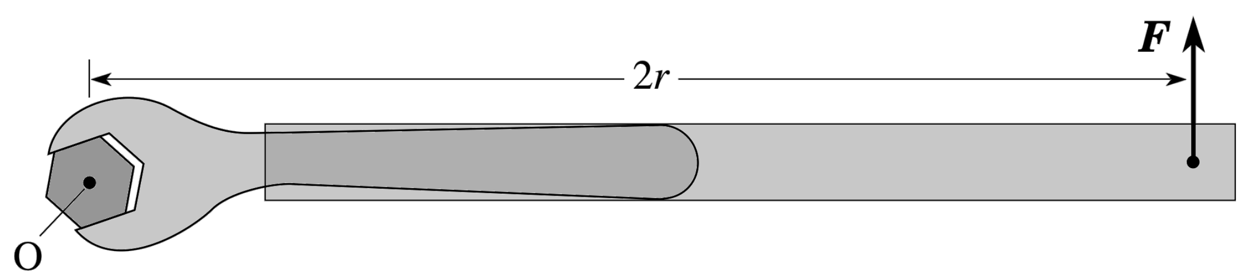
$$T = F \times r$$




$$T = 2F \times r$$

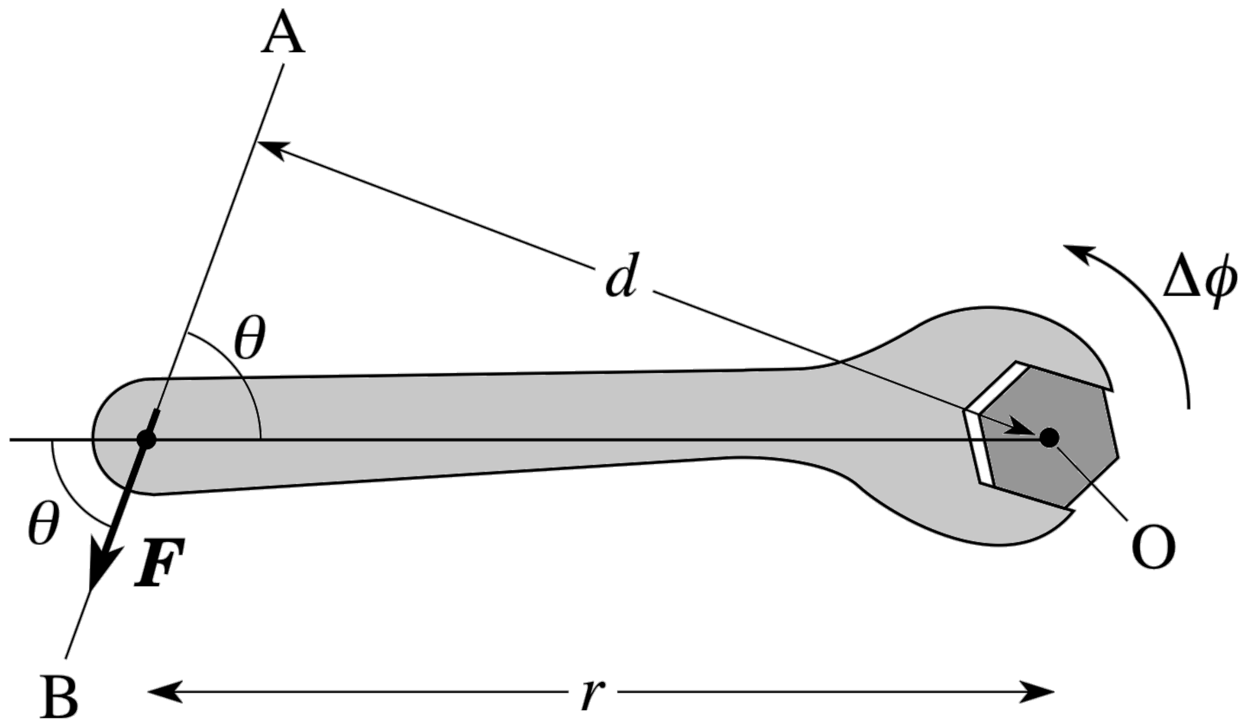



$$T = F \times 2r$$



# Torque

To calculate the torque, we need to find the the perpendicular distance

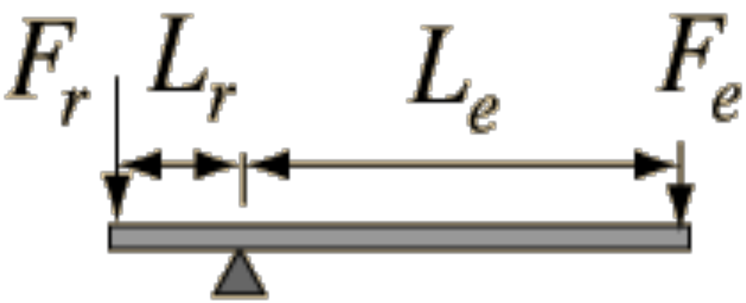



$$T = F \times d \quad \text{where} \quad d = r\sin(\theta)$$

$$\Rightarrow T = F \times r\sin(\theta)$$

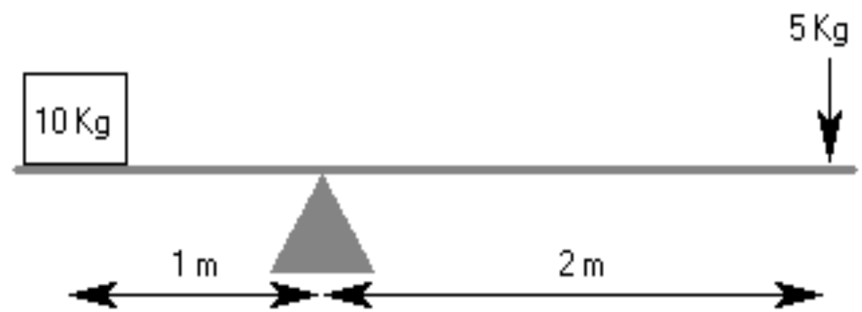
# Simple lever

Torques around pivot on LHS and RHS must balance




$$\Rightarrow F_r \times L_r = F_e \times L_e$$

$$\Rightarrow \frac{F_r}{F_e} = \frac{L_e}{L_r} = MA$$

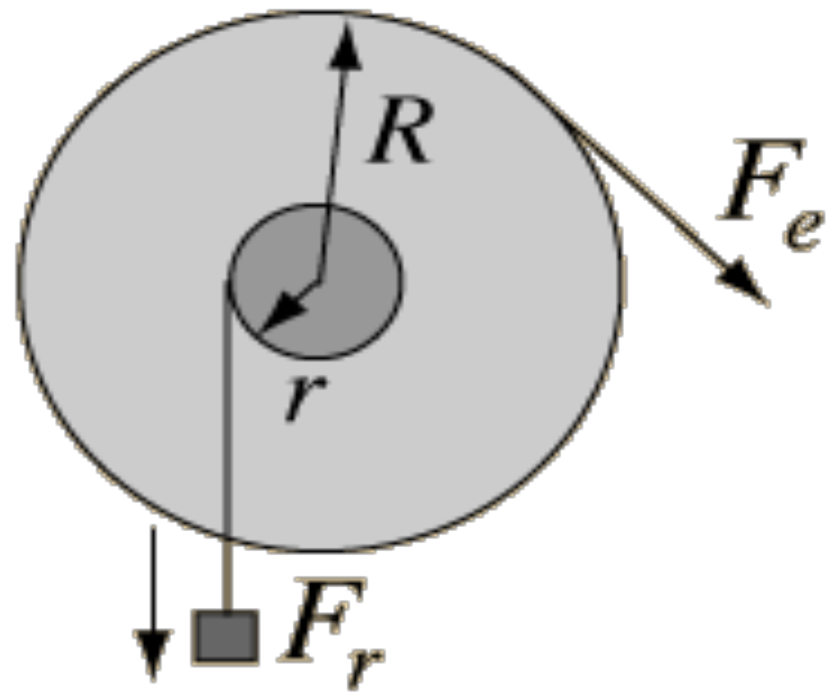



# Simple pulley

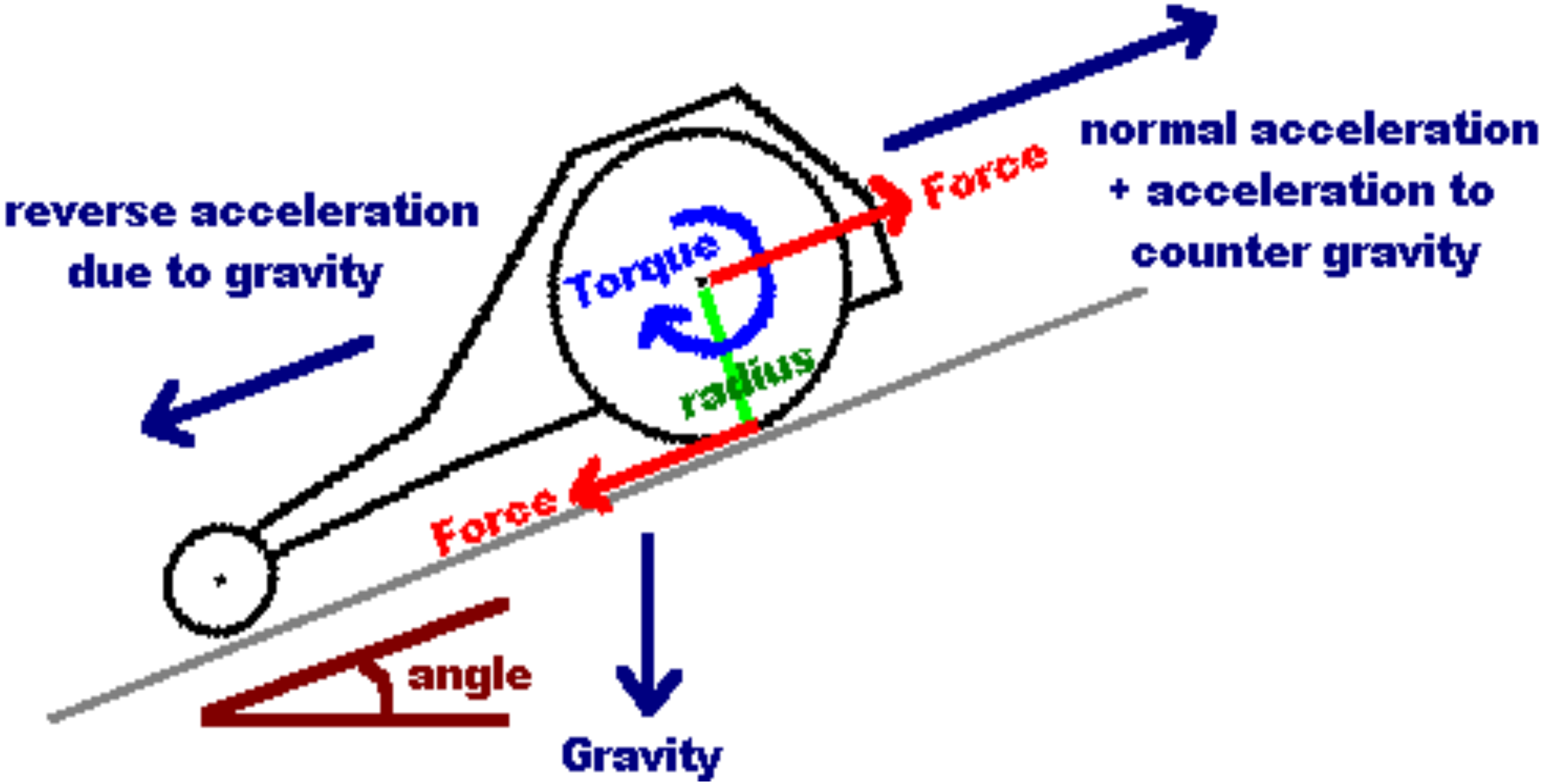
Torques around center of pulley must balance

$$\Rightarrow rF_r = RF_e$$

$$\Rightarrow \frac{F_r}{F_e} = \frac{R}{r} = MA$$



# Torque needed to drive buggy up hill




Need to compute torque to drive uphill

- Force = mg sin(angle)
- Torque = mg sin(angle) * radius