



# Manipulation with Cozmo

- No hands → No grasping.
- What can we do?
  - Exploit constraints in the environment.
  - Use the environment to supply additional contact points (e.g. walls).
  - Use a second robot to provide a second contact point.
  - Specialized lift attachments.

# Constraints

- Constraints can be your friend!
  - Upside: Use the environment and the object itself to your advantage.
  - Downside: Requires planning and *accurate* modeling
- Example: Part Orientation
  - Can position/orient an 'L' shaped part with unknown initial configuration using nothing more than an actuated tray — no sensors!

# Constraints Are Your Friend

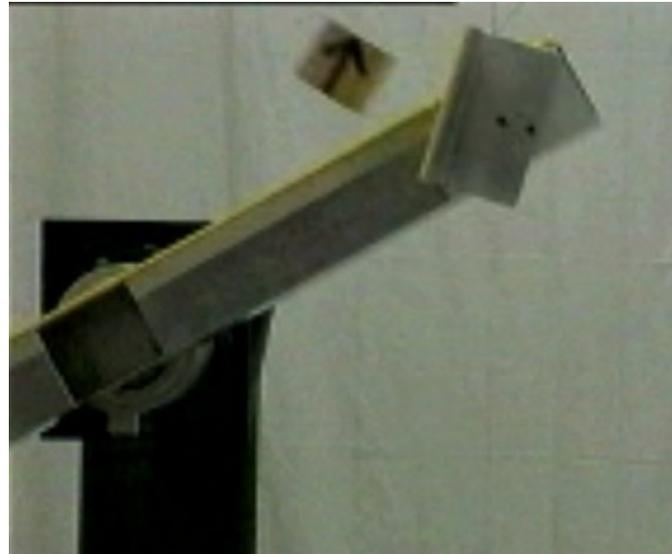
- Example: Part Orientation



Fujimori, T., *Development of Flexible Assembly System "SMART"*  
Video of Sony SMART Cell demo system by Wes Huang  
CMU Manipulation Lab

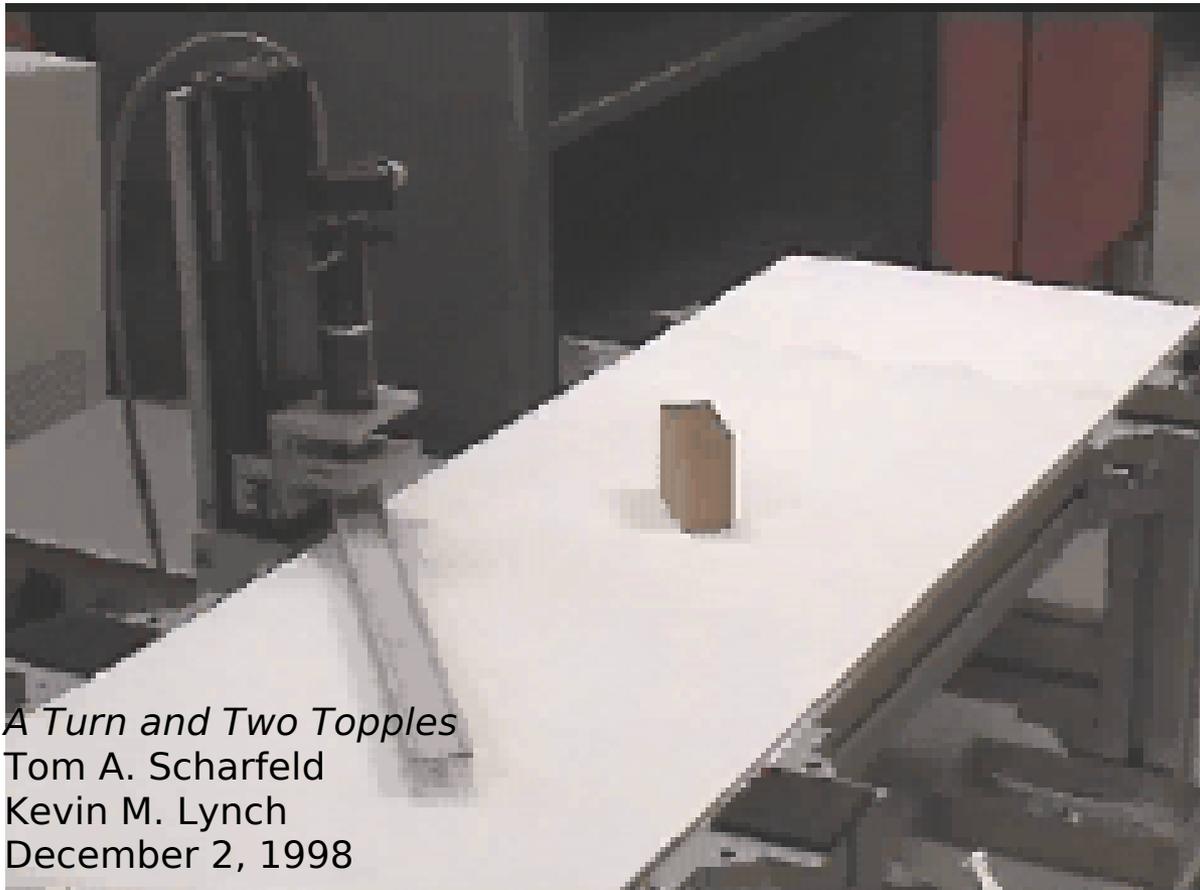
# Constraints Are Your Friend

- Example: Throwing (Kevin Lynch)



# Constraints Are Your Friend

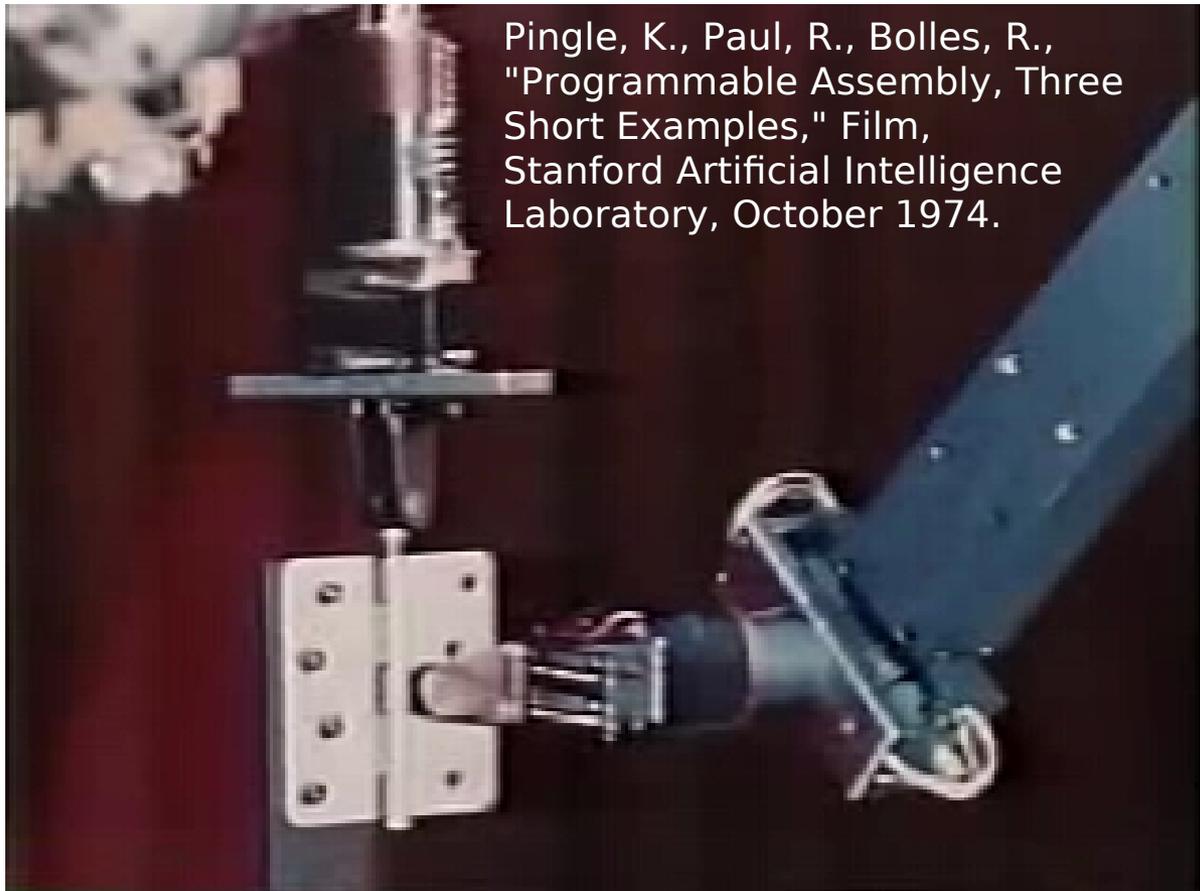
- 2 DOF Arm over a conveyor belt (2JOC)



*A Turn and Two Topples*  
Tom A. Scharfeld  
Kevin M. Lynch  
December 2, 1998

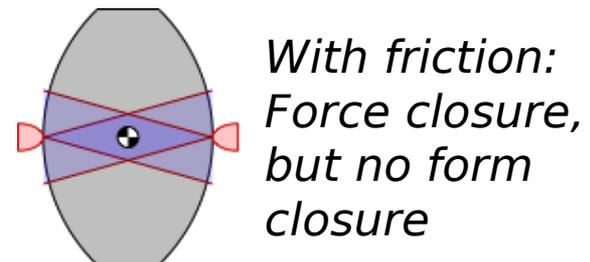
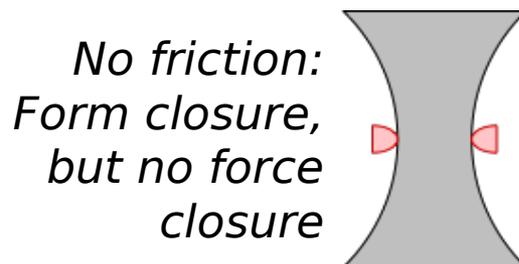
# Constraints Are Your Friend

- Example: Hinge Assembly



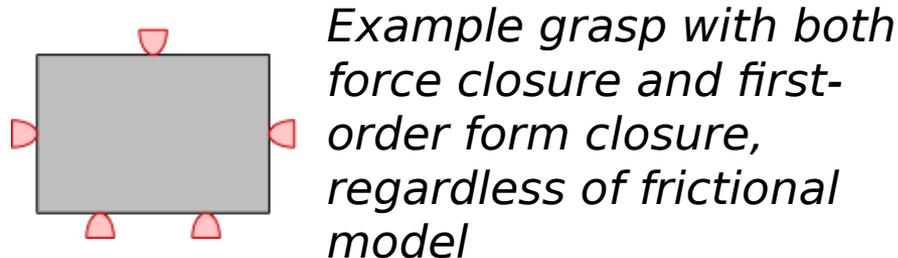
# Grasping

- What does it mean to “hold” something?
  - *Form closure*: object is “secure” — can’t move without moving a contact point
  - *Force closure*: can apply any desired force
- Not necessarily the same thing — depends on your friction model (see later slides).



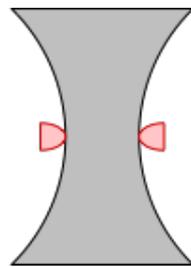
# Grasping

- Form closure is defined in increasing *orders*: position, velocity, acceleration, etc.
- Force closure does not have orders (you have it or you don't)
- Frictionless force closure equates to *first-order* (positional) form closure

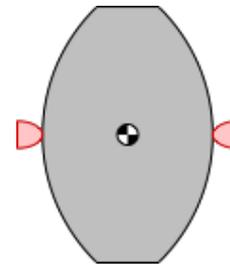


# Grasping

- Original examples do not have force closure
- Left figure can be moved infinitesimally up or down, although cannot be in motion vertically (so it has second-order form closure)



*With no friction,  
neither example  
has force closure  
nor  
first-order form  
closure*



# Closure Is Not Essential



# Grasping

- What does it mean to “hold” something?
  - *Form closure*: object is “secure” — can’t move without moving a contact point
  - *Force closure*: can apply any desired force
  - *Equilibrium*: can resist environmental forces (gravity)
  - *Stability*: how much variance from the environment can be tolerated and still maintain equilibrium

# Taxonomy of Contacts

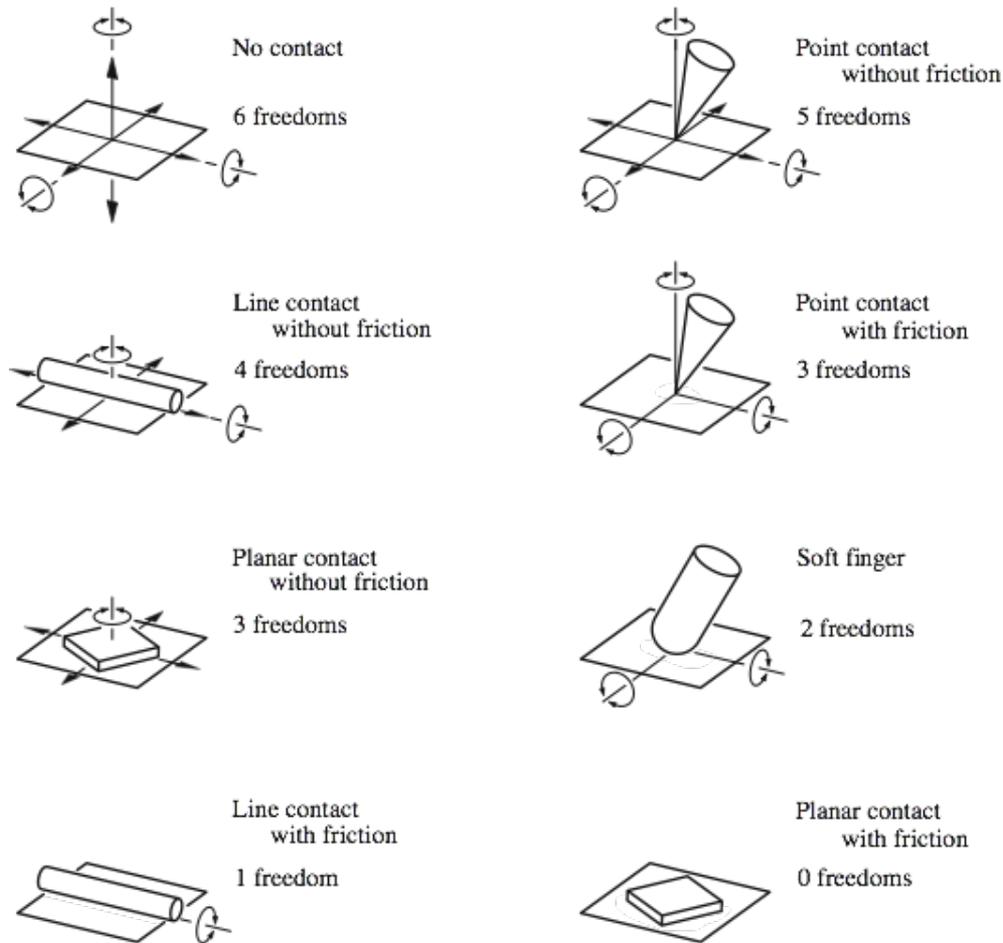
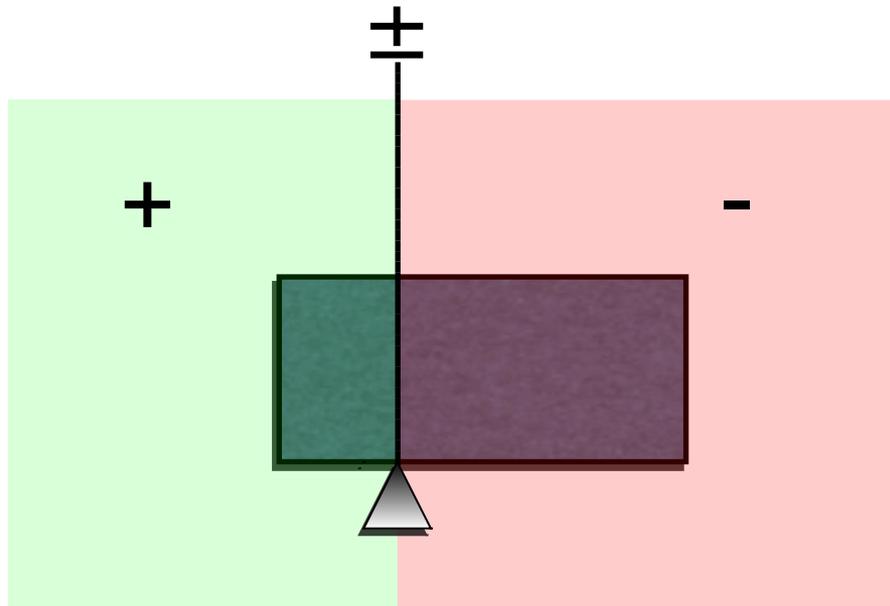


Figure 4.8 - Mason, *Mechanics Of Robotic Manipulation*

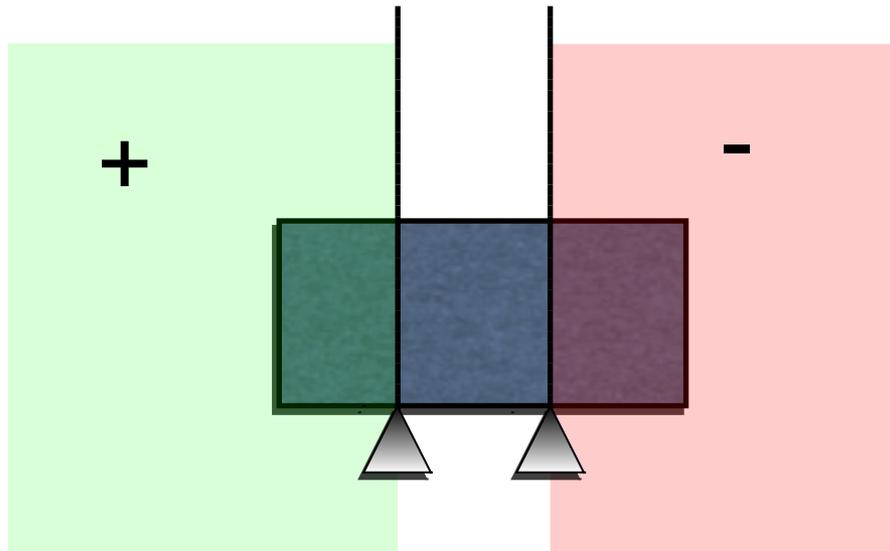
# Grasp Analysis: Reuleaux's Method

- For each constraint, divide the plane into areas which can hold positive or negative centers of rotation (IC's - instantaneous centers)



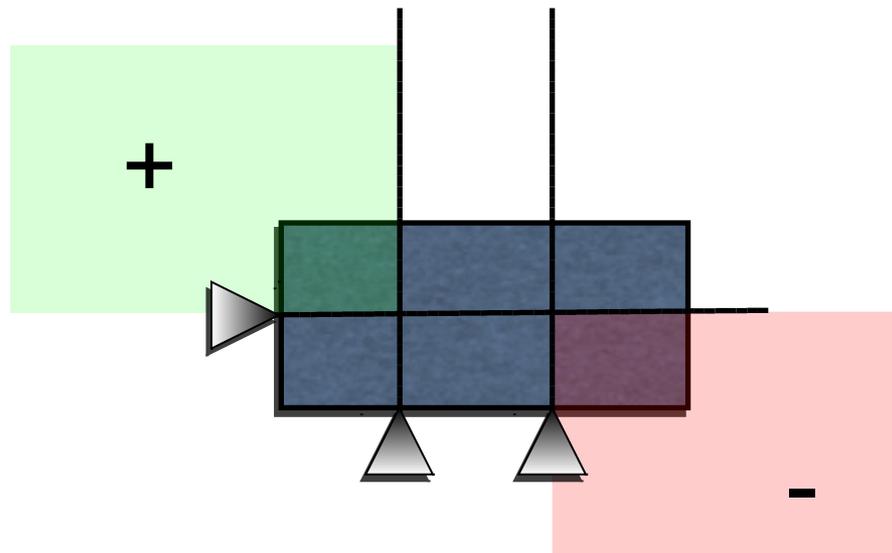
# Grasp Analysis: Reuleaux's Method

- Intersect common regions



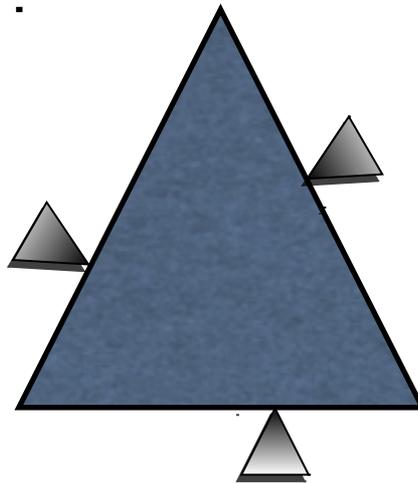
# Grasp Analysis: Reuleaux's Method

- Intersect common regions



# Grasp Analysis: Reuleaux's Method

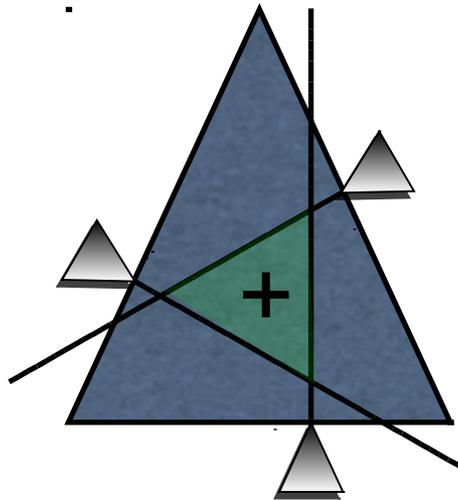
- Another example:



- Is this completely constrained?

# Grasp Analysis: Reuleaux's Method

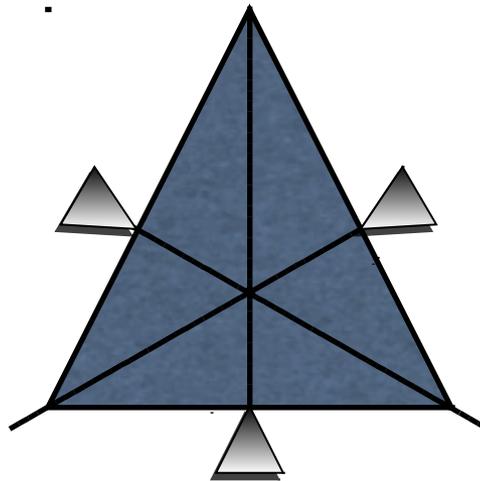
- Another example:



- Can spin counter-clockwise around area in the middle — but not clockwise!

# Grasp Analysis: Reuleaux's Method

- How about now?



- Common intersections may indicate, but *do not guarantee*, that rotation is possible

# Grasp Analysis: Reuleaux's Method

- Reuleaux's Method is good for humans, not so good for machines
- Doesn't extend to three dimensions
- Analytical solution would require a lecture unto itself
  - 16-741: Mechanics of Manipulation
  - Learn about screws, twists, wrenches, and moments

# Friction: Coulomb's Law

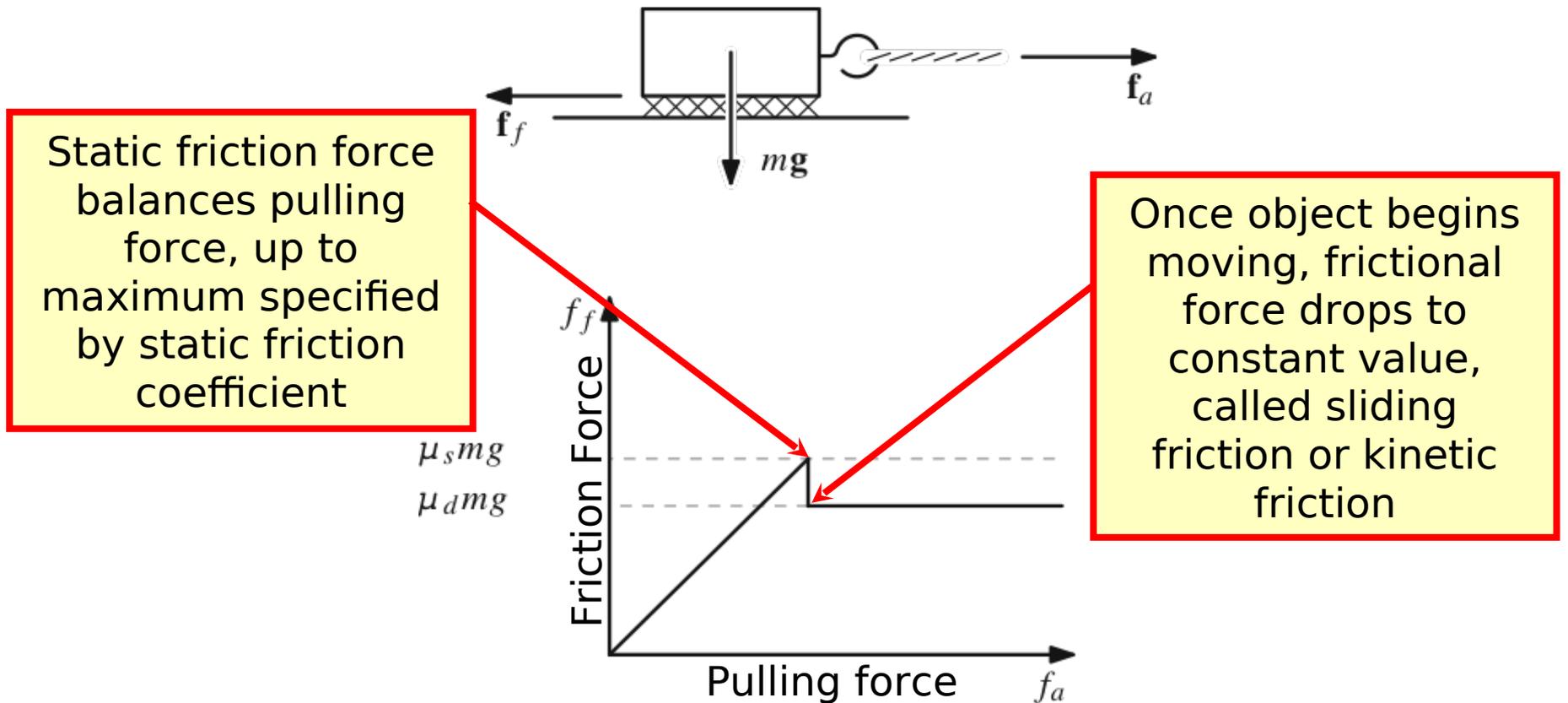


Figure 6.1 - Mason, Mechanics Of Robotic Manipulation

# Friction: Coulomb's Law

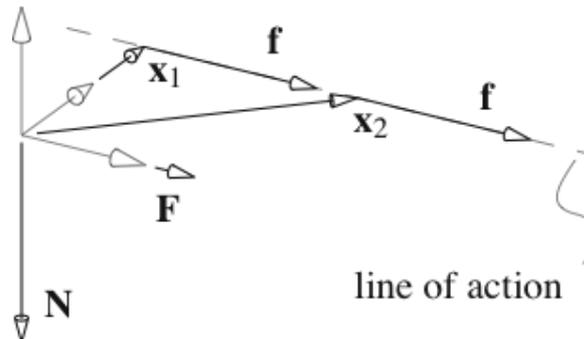
- For common tasks, independent of velocity and surface area
  - With extreme pressures, coefficient rises
  - With extreme velocities, coefficient drops
- Coefficients of friction are different for every pair of surfaces — table lookup
  - also differ for every change in temperature, humidity, dust/dirt, vibration, celestial alignment, etc. — not terribly accurate

# Friction within Joints

- Static friction is a headache for fine motor control
  - motor has to ramp up power to overcome static friction within gears, but as soon as it succeeds in doing so, it's now providing too much power and will “jump” to life.
  - this is the fundamental reason you see an Aibo robot's joints twitch from time to time
  - the higher the gear ratio, the bigger the problem

# Computing with Forces

- Forces are defined by a line through space, and a magnitude
- usually represented by a vector and a point
- but the point is not unique — any point along the vector is equally valid (“line of action”)

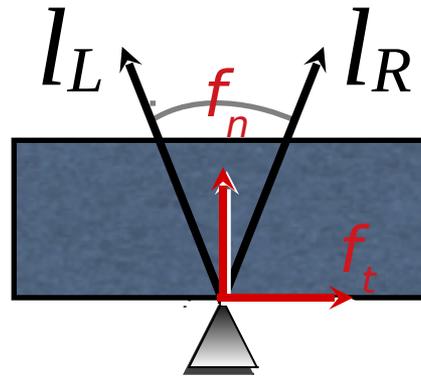


*Figure 5.1 - Mason,  
Mechanics Of Robotic Manipulation*

$$2 \tan^{-1} \mu$$

# Friction with Objects

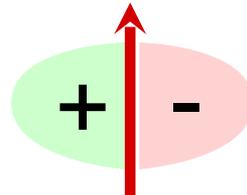
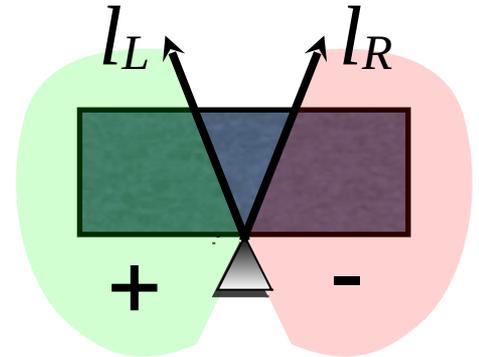
- Now we can define a friction cone:



- Edges of the cone define maximum angle allowed for forces without slippage
- If you break applied force into normal force  $f_n$  and tangential force  $f_t$ , friction cone is defined as  $|f_t| \leq \mu |f_n|$ , with interior angle  $2 \tan^{-1} \mu$

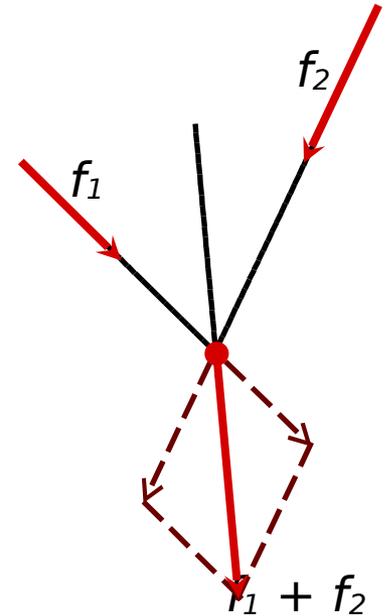
# Friction with Objects

- Remember Reuleaux's Method?
- Works with friction cones as well
- Now we're analyzing forces, not displacements, *a different interpretation!* (be careful about trying to mix them...)
- Only forces which agree with the all of the contacts' constraints can be applied by the contact(s):

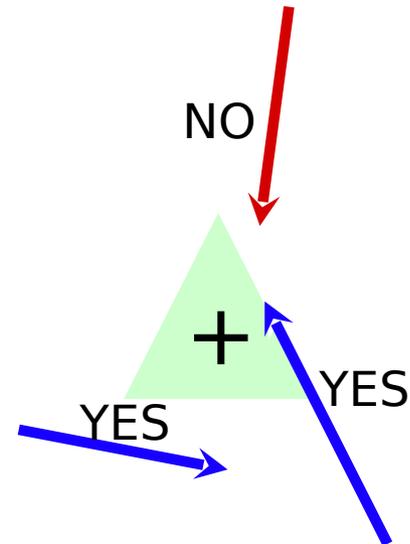
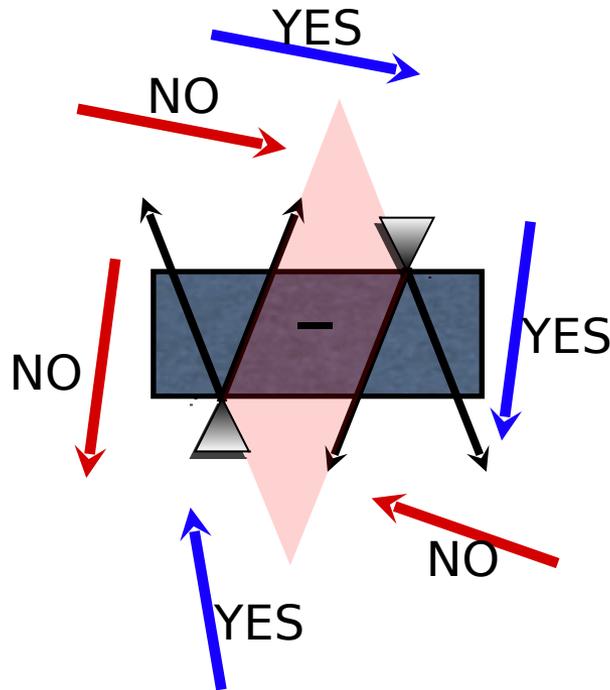


# Combining Forces

- Adding multiple contacts allows you to apply any force in the linear span of their friction cones
- Remember that forces act along a line through space
  - slide forces along line of action to intersection
  - Resultant force is the vector sum of the two forces, acting through common intersection

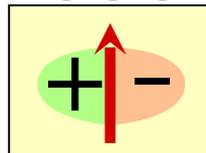


# Friction with Objects: Examples



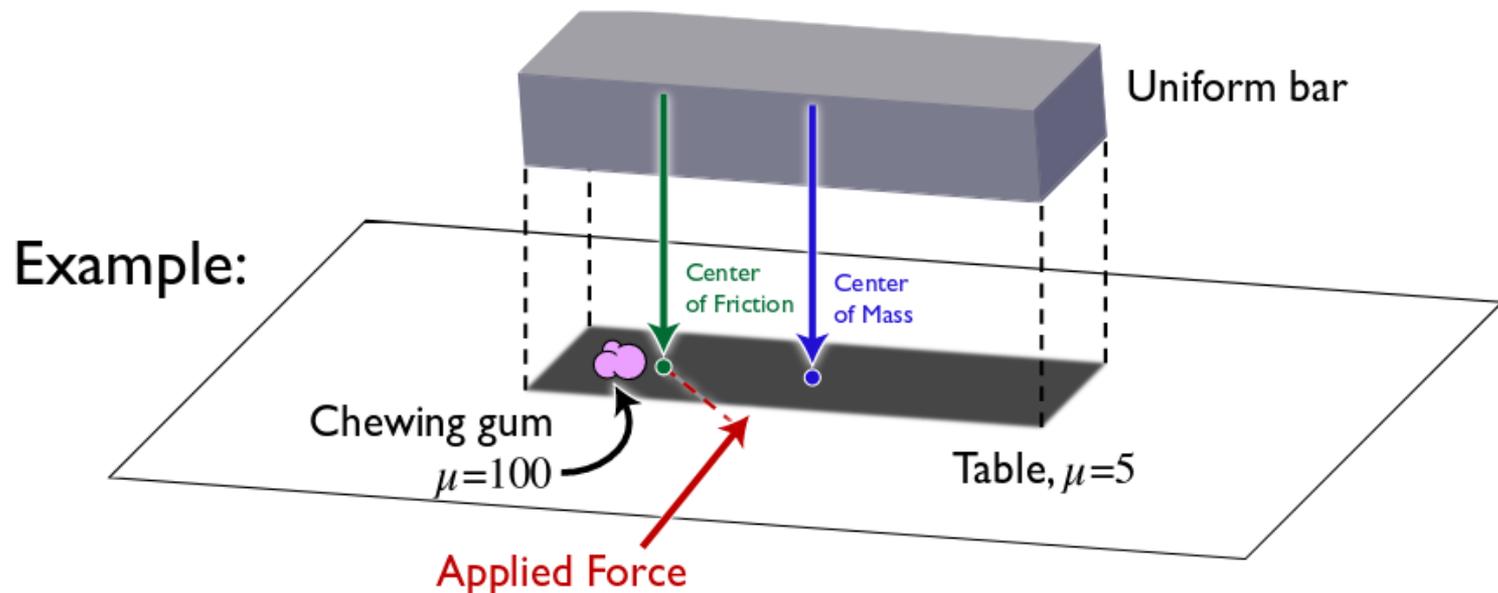
*Don't actually care about  
the object itself once contacts  
have been analyzed*

*For reference:*



# Center of Friction

- Similar to center of mass, center of friction is the integrated pressure over the support region
- Allows you to treat the interaction as a single contact



# Center of Friction

- Hard to model — with a rigid body, small variances completely throw off pressure distribution
- Ever play Jenga?



Photographer: Derek Mawhinney  
<http://en.wikipedia.org/wiki/Jenga>

# Applying Friction & Forces

- Use weight to flip brick
- Use wall to direct ball (extra arm)
- Get ball away from wall
- Use wall to align/direct brick
- Stand brick upright
- Insert objects without jamming or wedging