6.141: Robotics systems and science Lecture 13: Grasping and Manipulation

Lecture Notes Prepared by Daniela Rus
and Seth Teller
EECS/MIT
Spring 2011

Reading: Chapter3, Craig: Robotics

http://courses.csail.mit.edu/6.141/

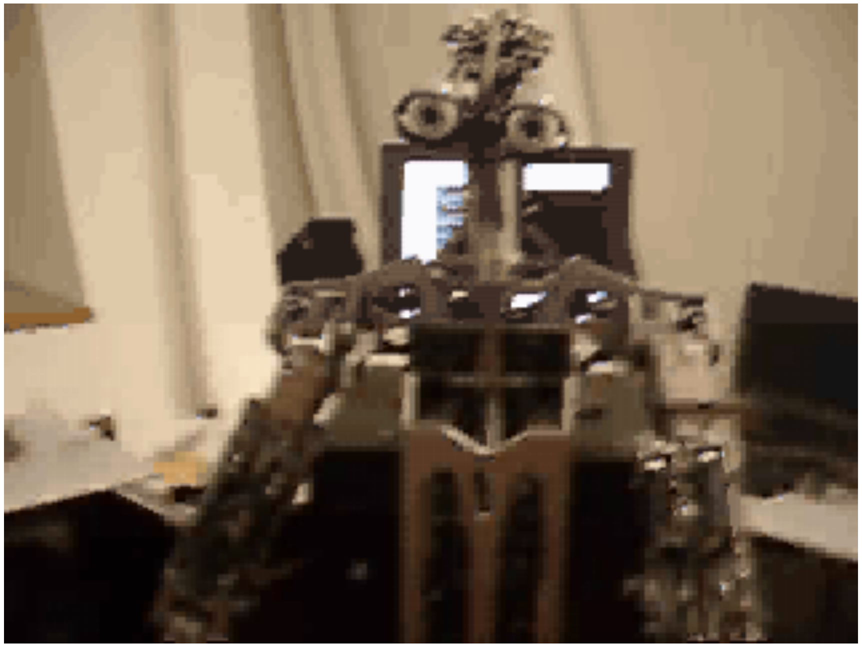
Challenge: Build a Shelter on Mars

Last 2 modules were about

- High-level planning
- Localization
- Challenge

Today

- Intro to debates
- Robot grasping
- Reading: chapters 3, 6



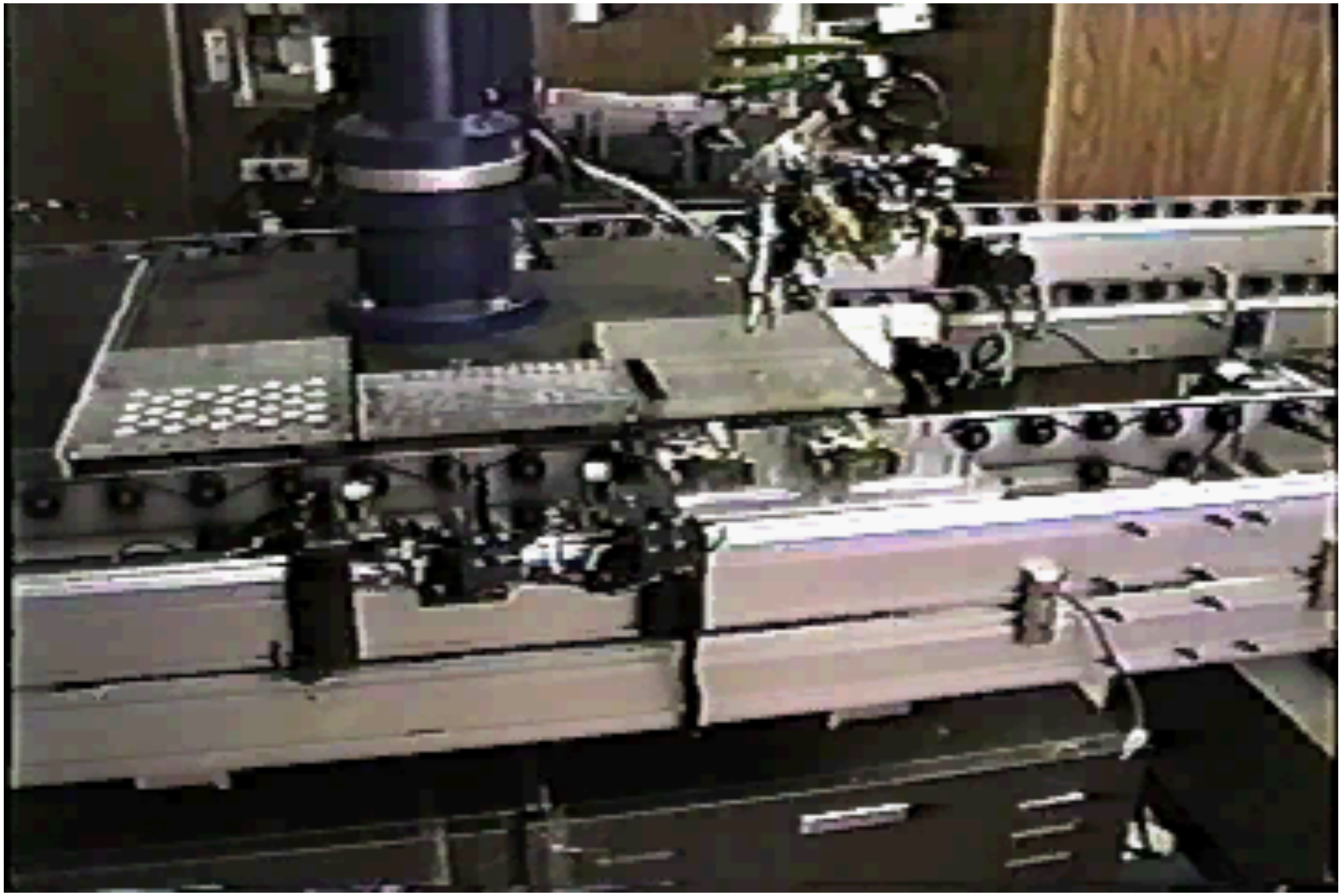
Debates

- Posted tomorrow on the Web, Pick topic by emailing kbates@csail.mit.edu by Friday April 2
- Debates shall be organized as follows:
  - **Constructive Speeches:** Affirmative: 7 min Negative: 7 min
  - **Rebuttal Speeches:** Affirmative: 3 min Negative: 3 min
  - **Discussion and Cross-Examination (4 minutes).**
    - When debating in teams, the constructive and rebuttal presentations may be shared by the team members.
    - Time will be kept using the briefing timer.
- Do not argue by authority, use technical arguments
- Rules of Evidence
  In debate, source citations of evidence must be stated the first time a source is used.
- Rules of Evidence Authenticity
  - Evidence must not be fabricated or distorted.
    - Fabrication means falsely representing a cited fact or statement of opinion as evidence; or intentional omission/addition of information within quoted material.
    - Distortion means misrepresentation of evidence or of citation which significantly alters meaning.

What is Manipulation?

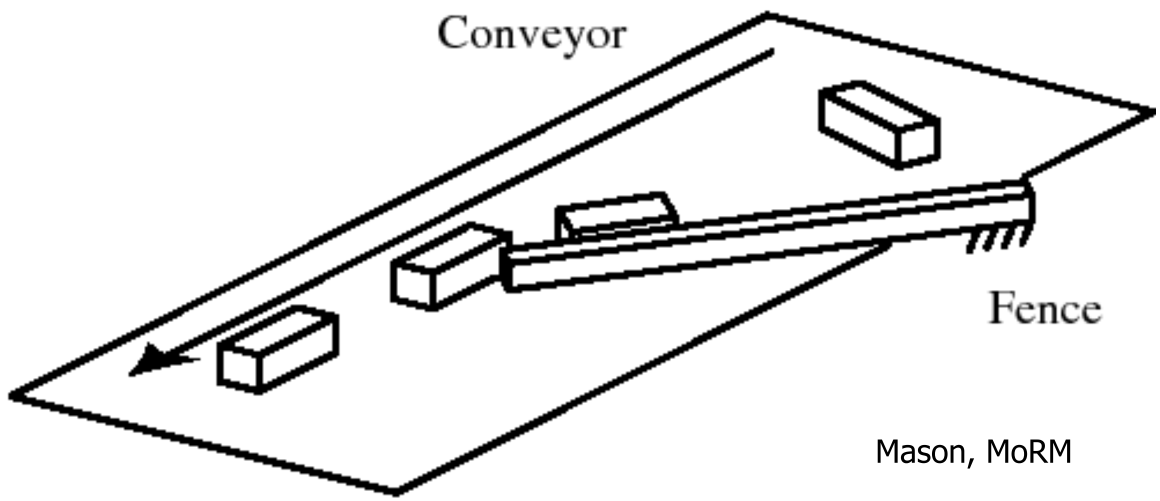
- Hayes, K.C. and Hayes, C.

Grasping and Manipulation



Fixturing

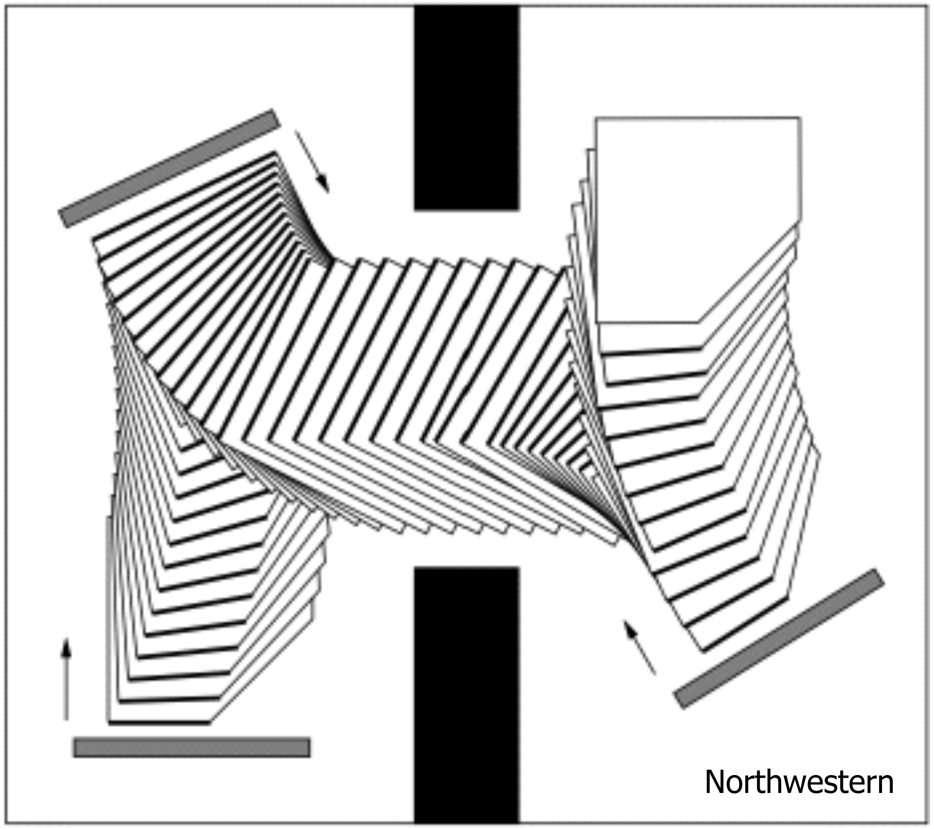
- Use of designed pegs, surfaces, prior knowledge of manipuland geometry to achieve desired pose



Mason, MoRM

Manipulation by Pushing

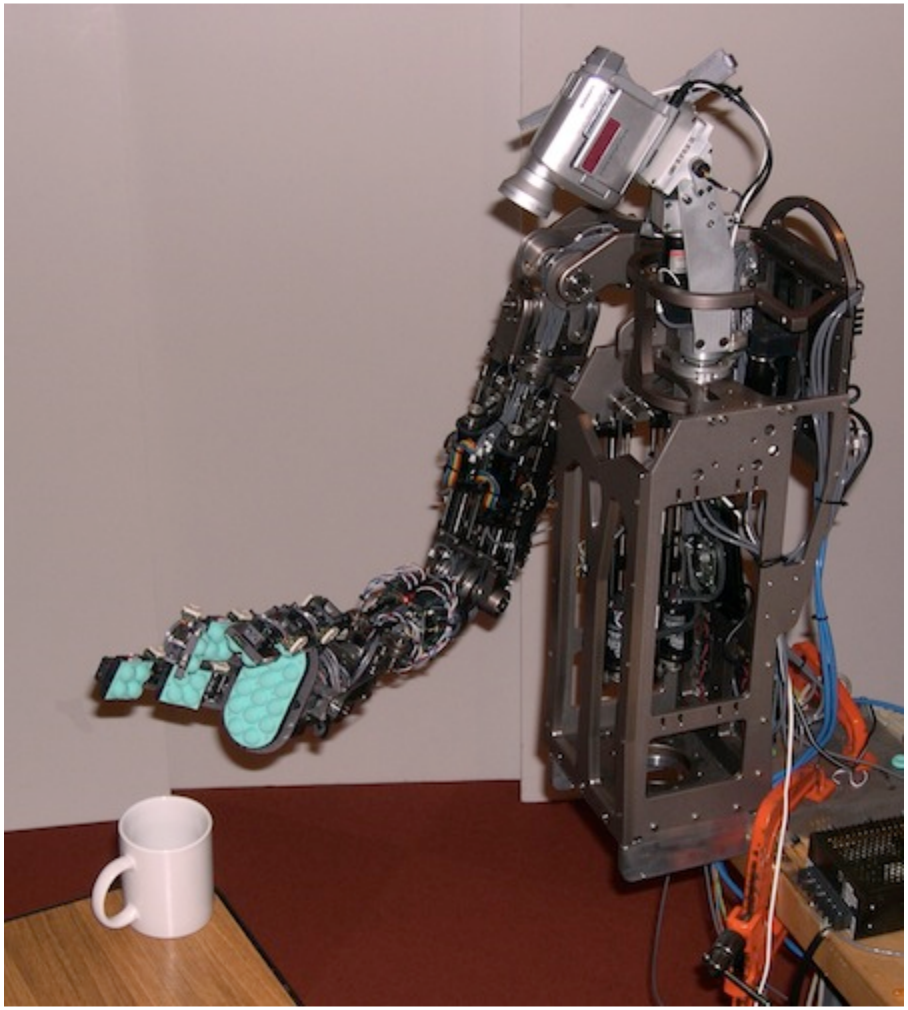
- Stable push:
  - Motions that keep object in line contact w/ manipulator



  - Motion planning, but with additional constraints

Soft-finger Manipulation

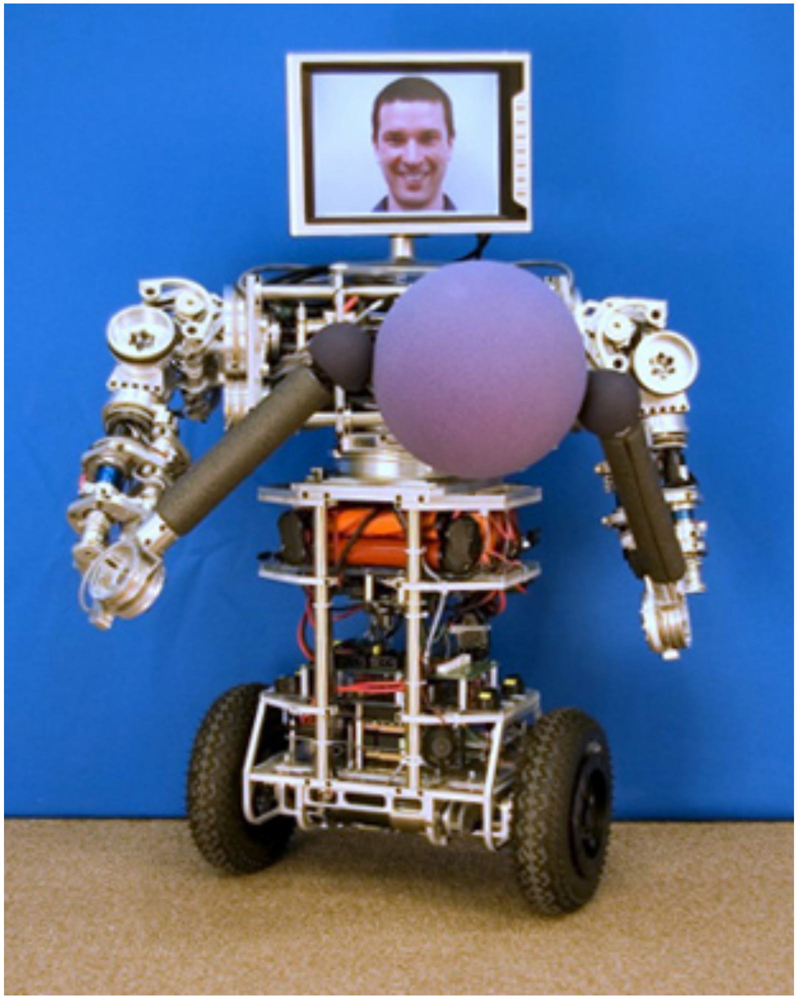
- Can exploit visual/tactile sensing & feedback



Obrero / MIT

Mobile, Two-handed Manipulation

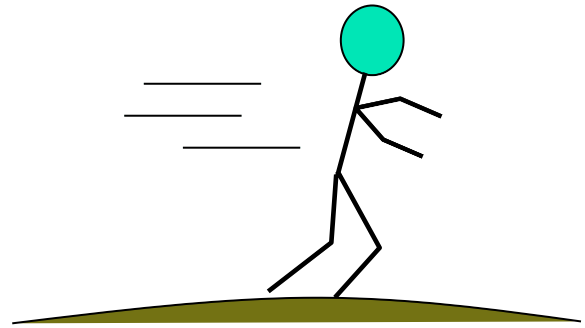
- Challenges: mass distribution; uncertainty



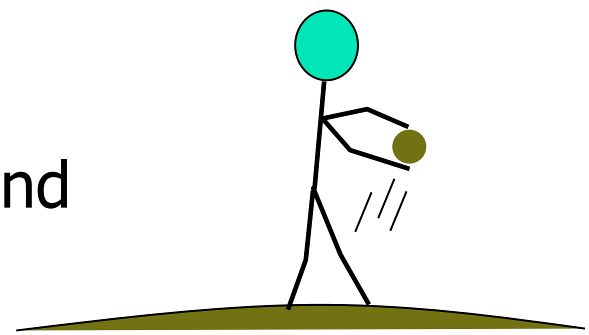
uBot / UMass Amherst

Mobility and Manipulation

- Mobility:
  - Earth is fixed
  - Legs apply forces to earth
  - Forces move body



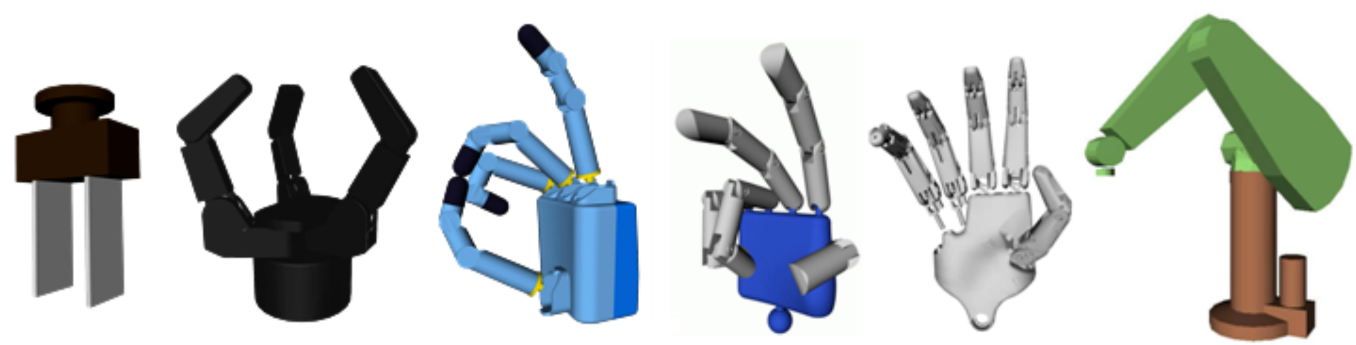
- Manipulation:
  - Body is fixed to earth
  - Arms apply forces to manipuland
  - Forces move manipuland



- Goal of Field: Mobile Manipulation
  - Use of limbs in concert to effect <u>coordinated motion</u> of body, limbs, and manipuland
  - Examples: Lifting a sandbag, throwing a baseball, shoveling snow, replacing a ceiling smoke detector

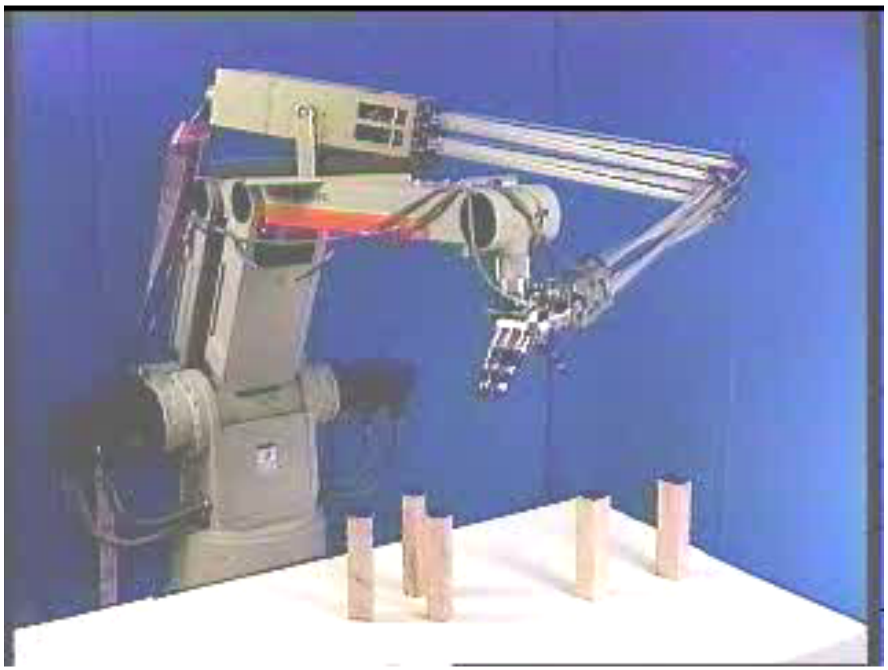
Robot Hands

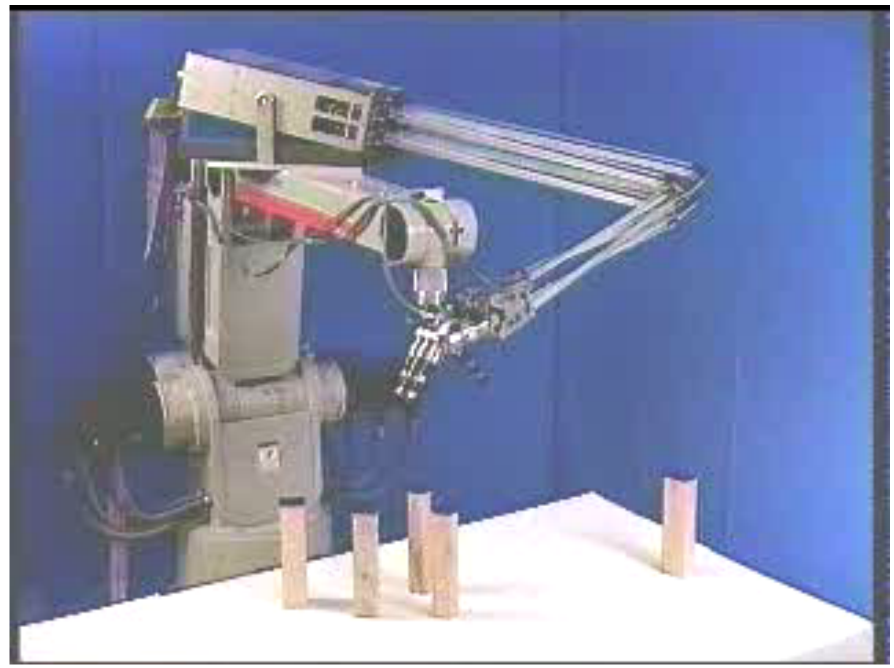
- End-effectors are the part of the robot that usually does manipulation
- Many designs...



Parallel Jaw | Barrett | DLR | Rutgers | Robonaut | Puma 560

Problems

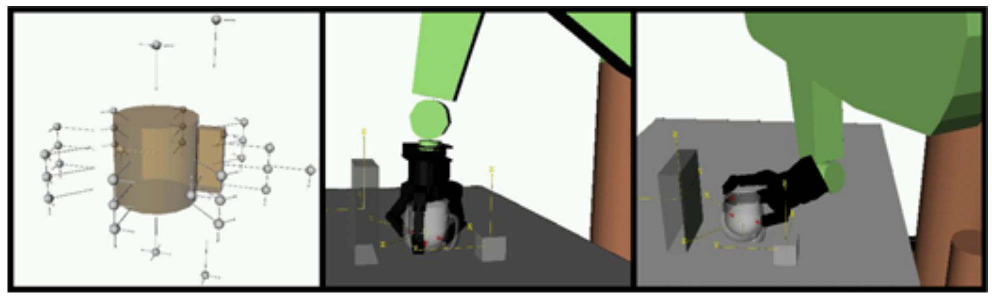




How does the robot reach for the object?
How does the robot grab the object?
How does the robot move the object?

Grasping

- Using end-effectors (fingers) to immobilize something relative to the hand
- Issues:



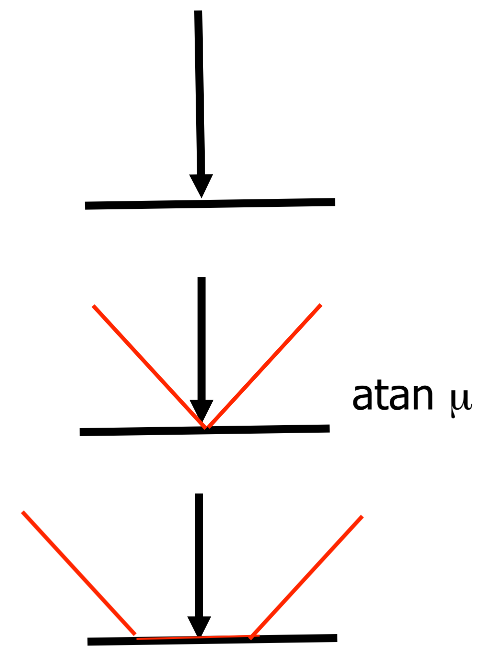
  - What contacts?
  - Where to place the contact points?
  - What grasp properties?

Grasp Types

- Force closure: fingers resist any external force
- Torque closure: fingers resist any external torque
- Equilibrium: the contact forces can balance the object weight and external forces

Finger types

- Point contact with friction
- Hardfinger Contact
- Softfinger Contact

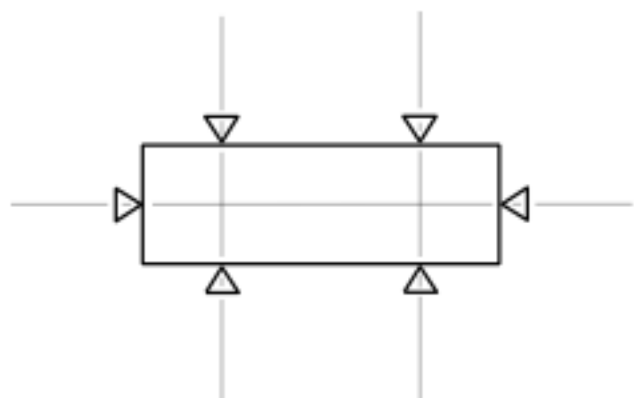


Issues in Grasp Design

- Existence: given an object and constraints determine if closure exist
- Analysis: given an object and contacts determine if closure applies
- Synthesis: given an object, find contacts that result in closure

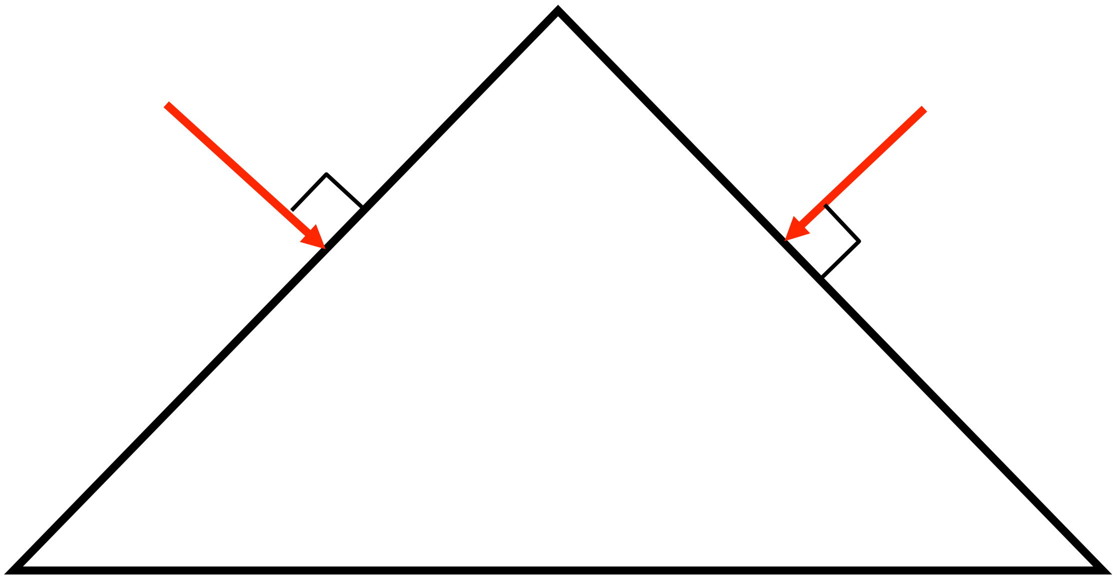
Existence

- Given an object, does it have a force-closure grasp?
- Theorem1 (Mishra, Schwartz, Sharir): for any bounded object that is not a surface of revolution a force closure grasp exists
- Theorem2 (Mishra, Schwartz, Sharir): at most 6 fingers in 2d, 12 fingers in 3d



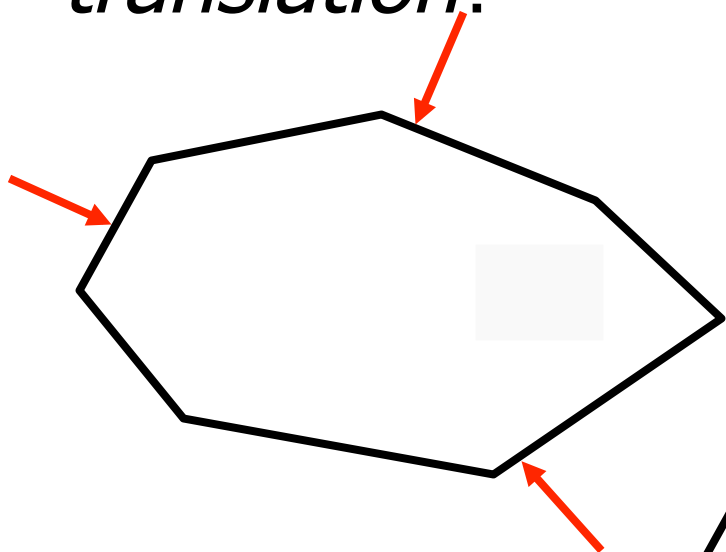
Frictionless Point Contacts

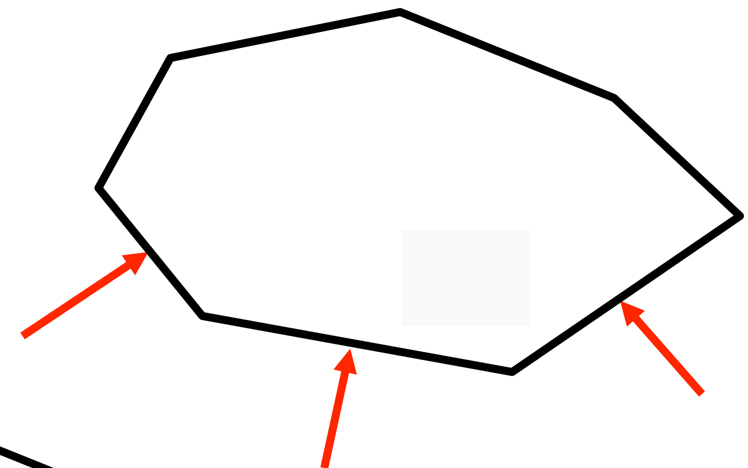
- Force must be normal to object boundary (why?)
- Force must point into object's interior

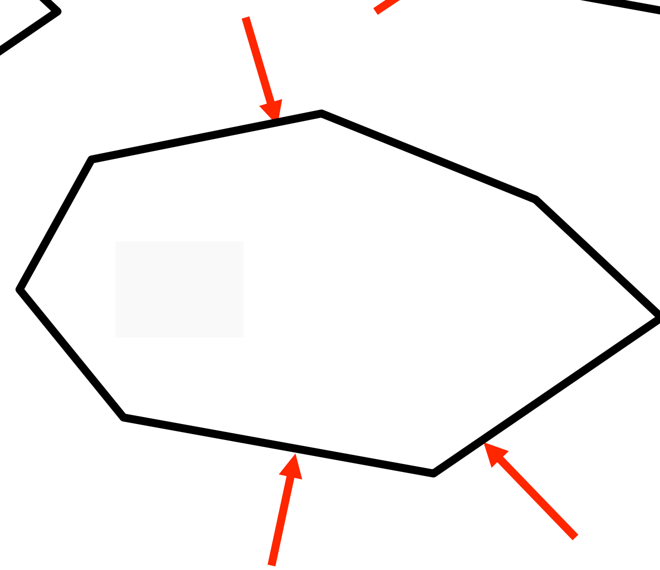


Force-Direction Closure

- Under what conditions will a set of point contact forces resist arbitrary planar *translation*?



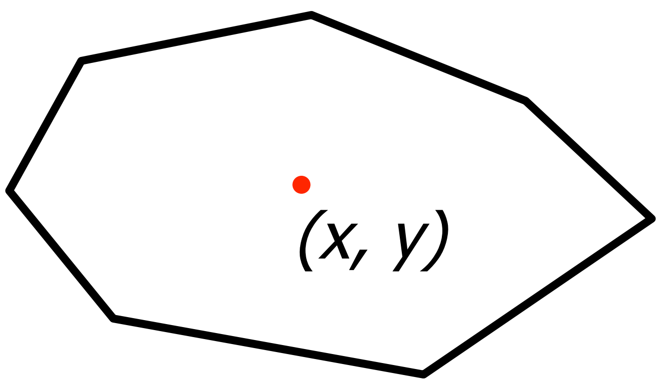




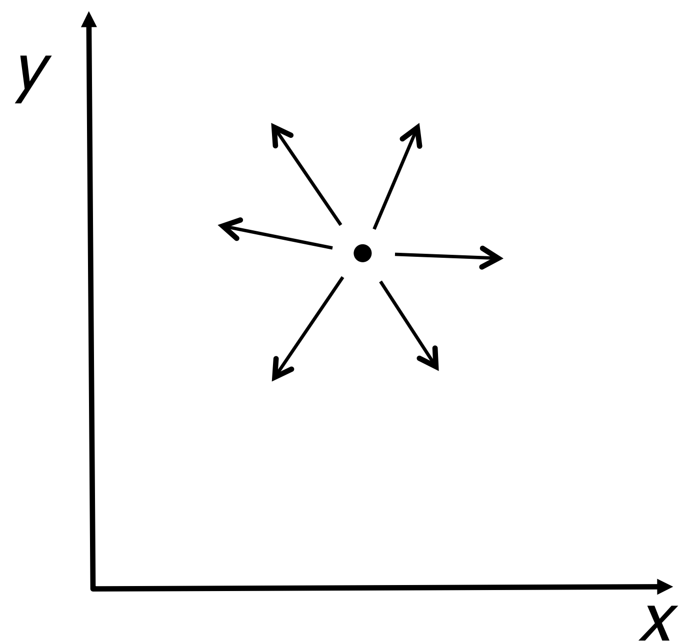
… What's going on?

How many contacts are needed?

- Analyze situation in c-space with DOF argument
  - First: how many c-space DOFs for object origin?



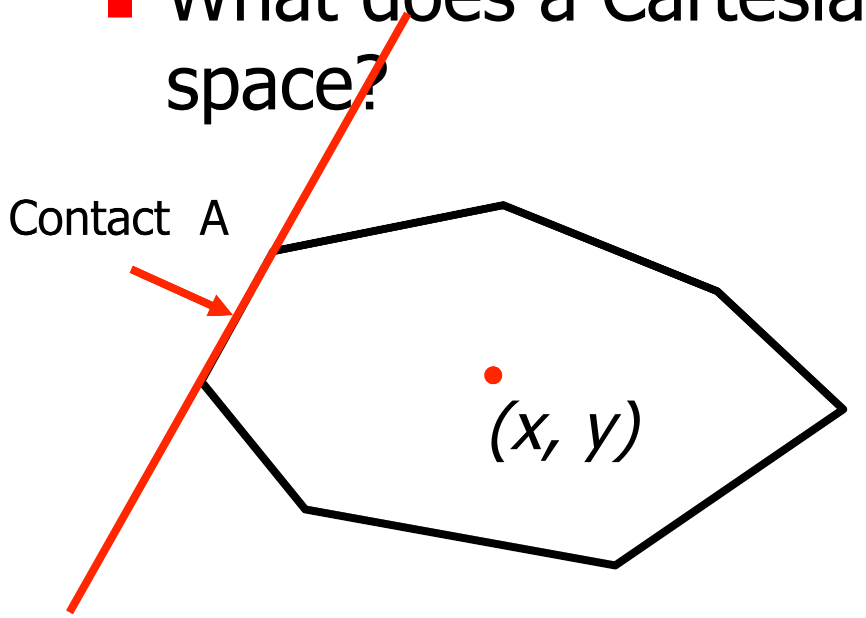
Cartesian space



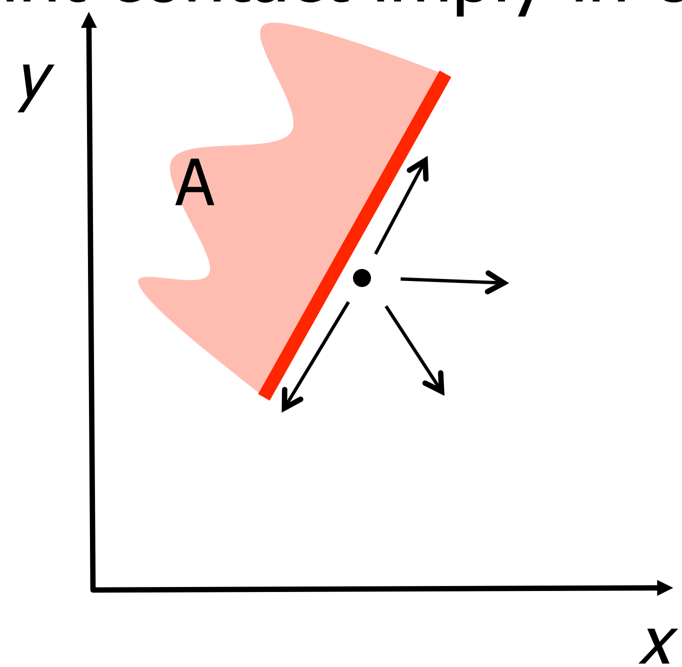
Configuration space

How many contacts are needed?

- Analyze situation in c-space with DOF argument
  - What does a Cartesian point contact imply in c-space?



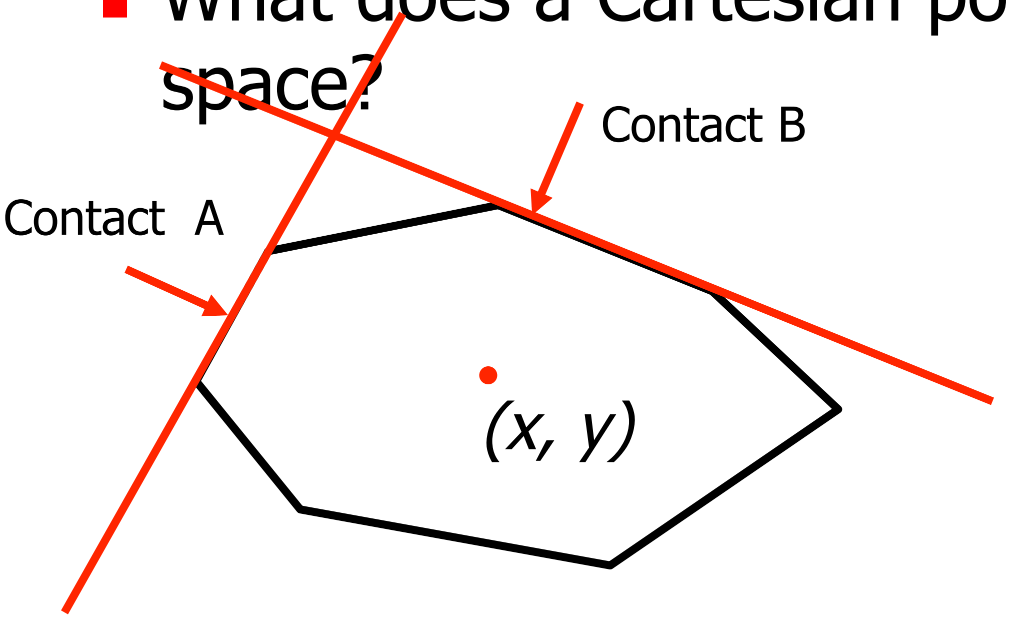
Cartesian space



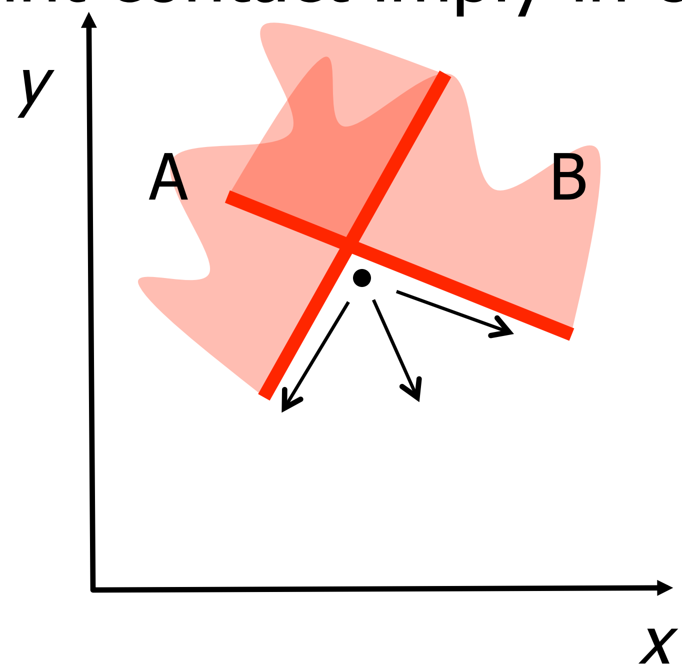
Configuration space

How many contacts are needed?

- Analyze situation in c-space with DOF argument
  - What does a Cartesian point contact imply in c-space?



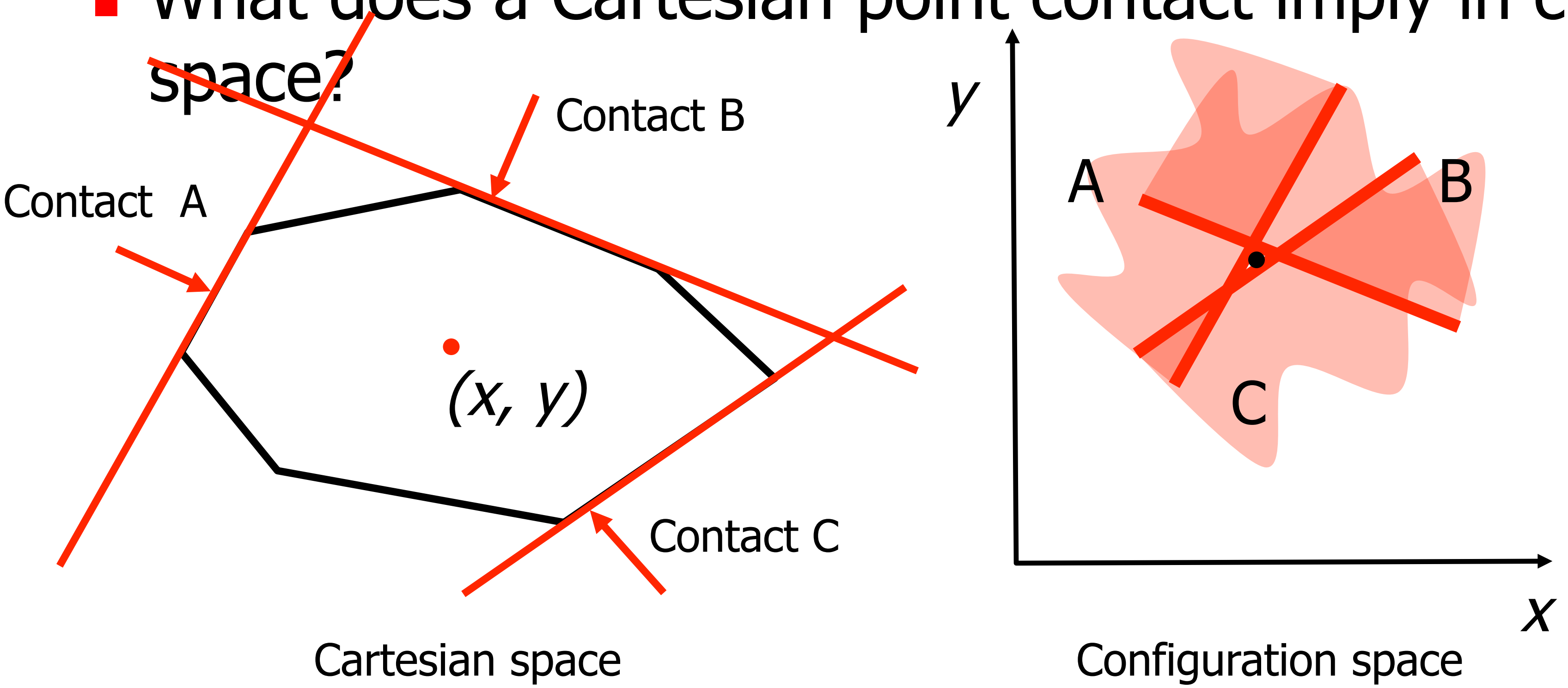
Cartesian space



Configuration space

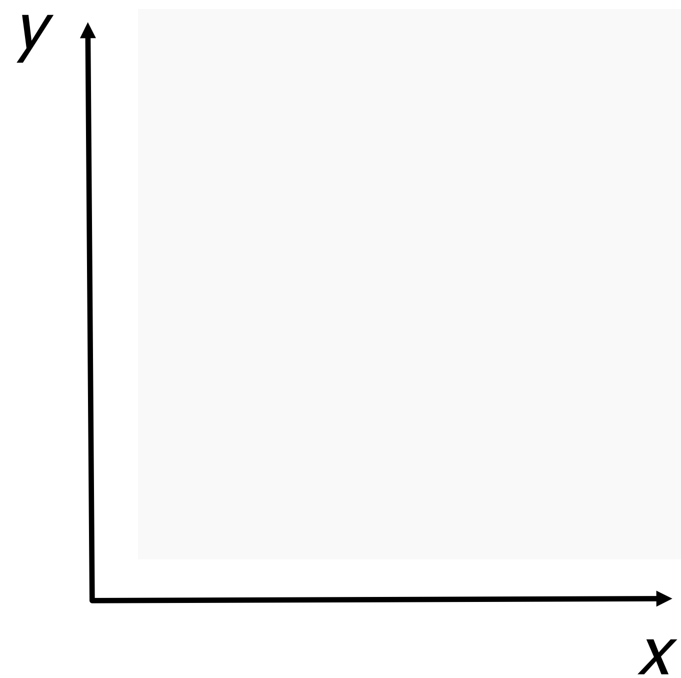
How many contacts are needed?

- Analyze situation in c-space with DOF argument
  - What does a Cartesian point contact imply in c-space?



DOF Counting for Translation

- Conclude that contacts are needed in general
  - Are there situations in which more are required?



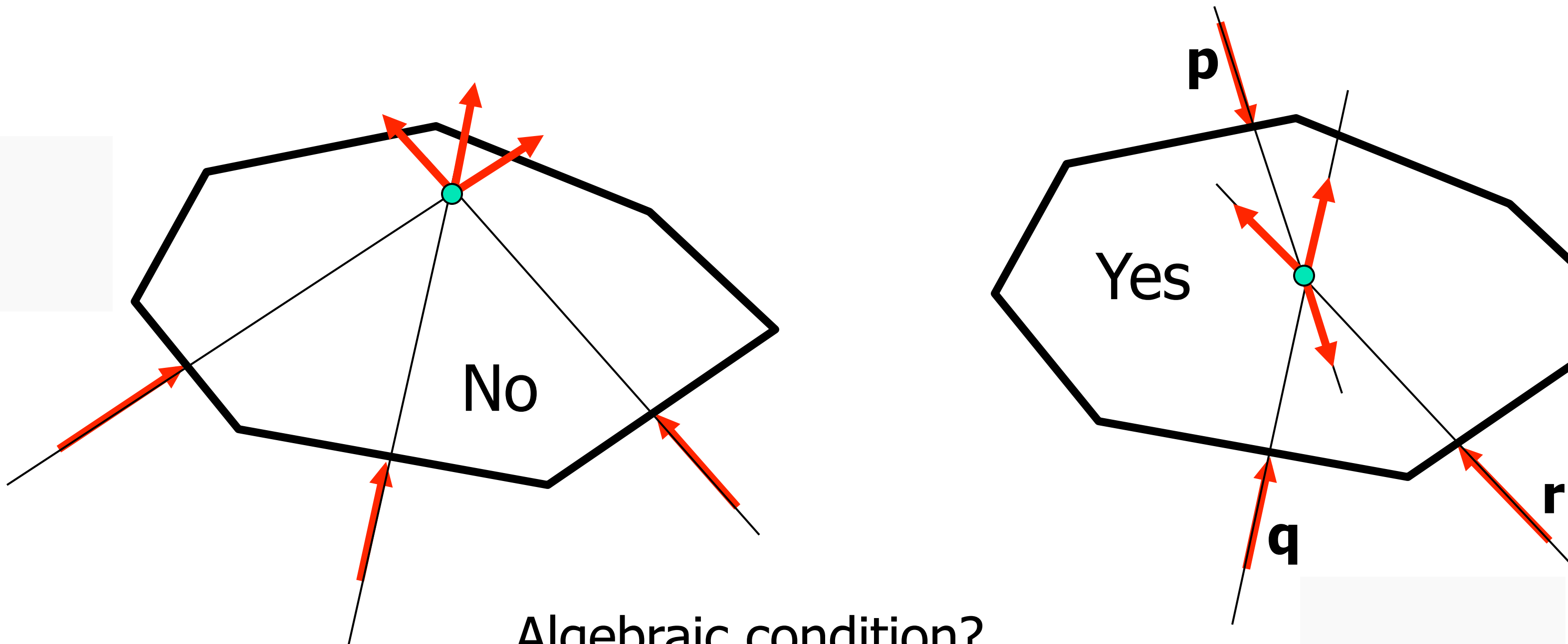
Cartesian space

Configuration space

  - Example of geometric

Conditions for Force-Direction Closure

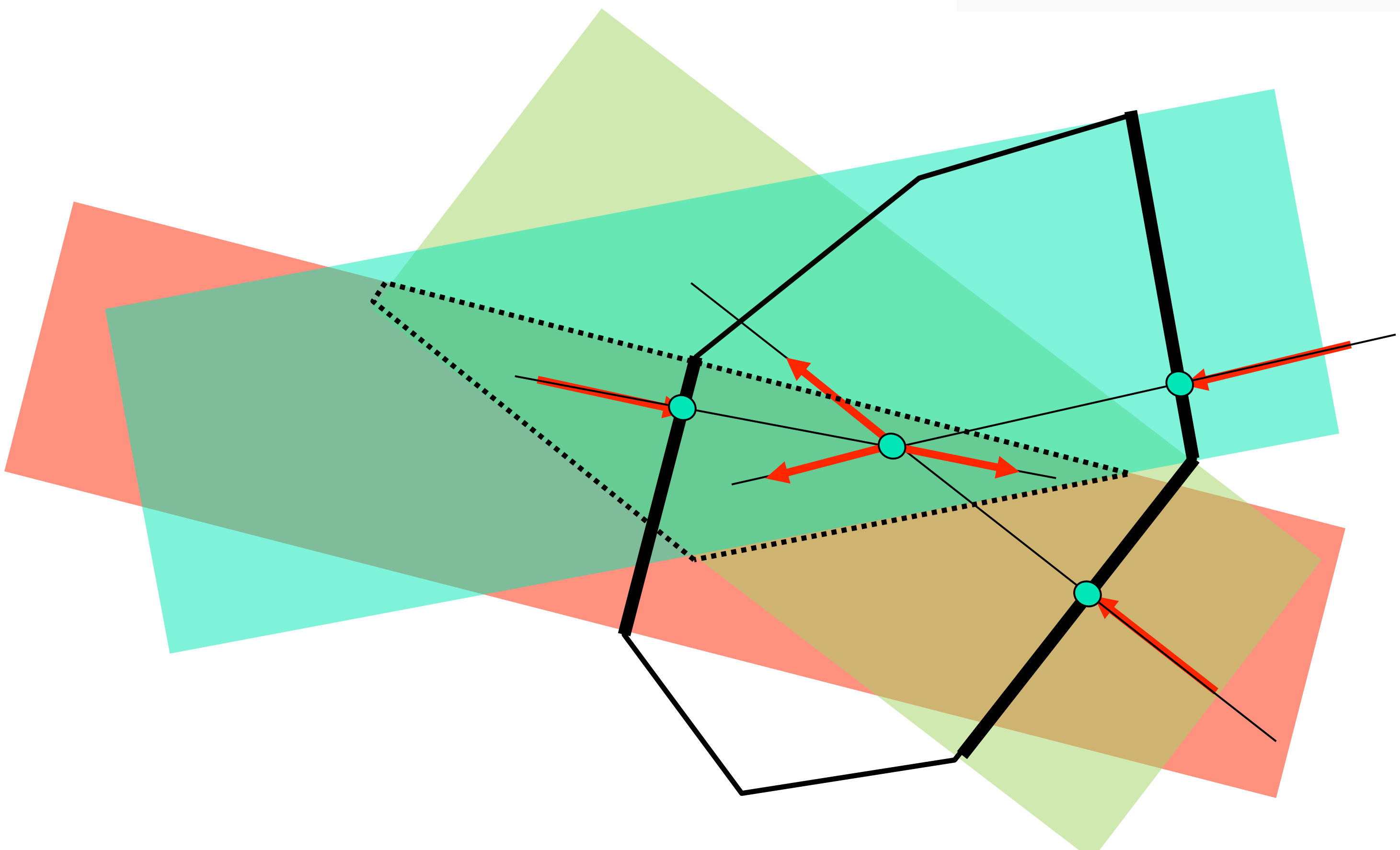
- Force vectors must
- Some positive combination of forces



Algebraic condition?
For force vectors **p**, **q**, **r**,
there must exist $\alpha, \beta, \gamma > 0$
s.t. **0**

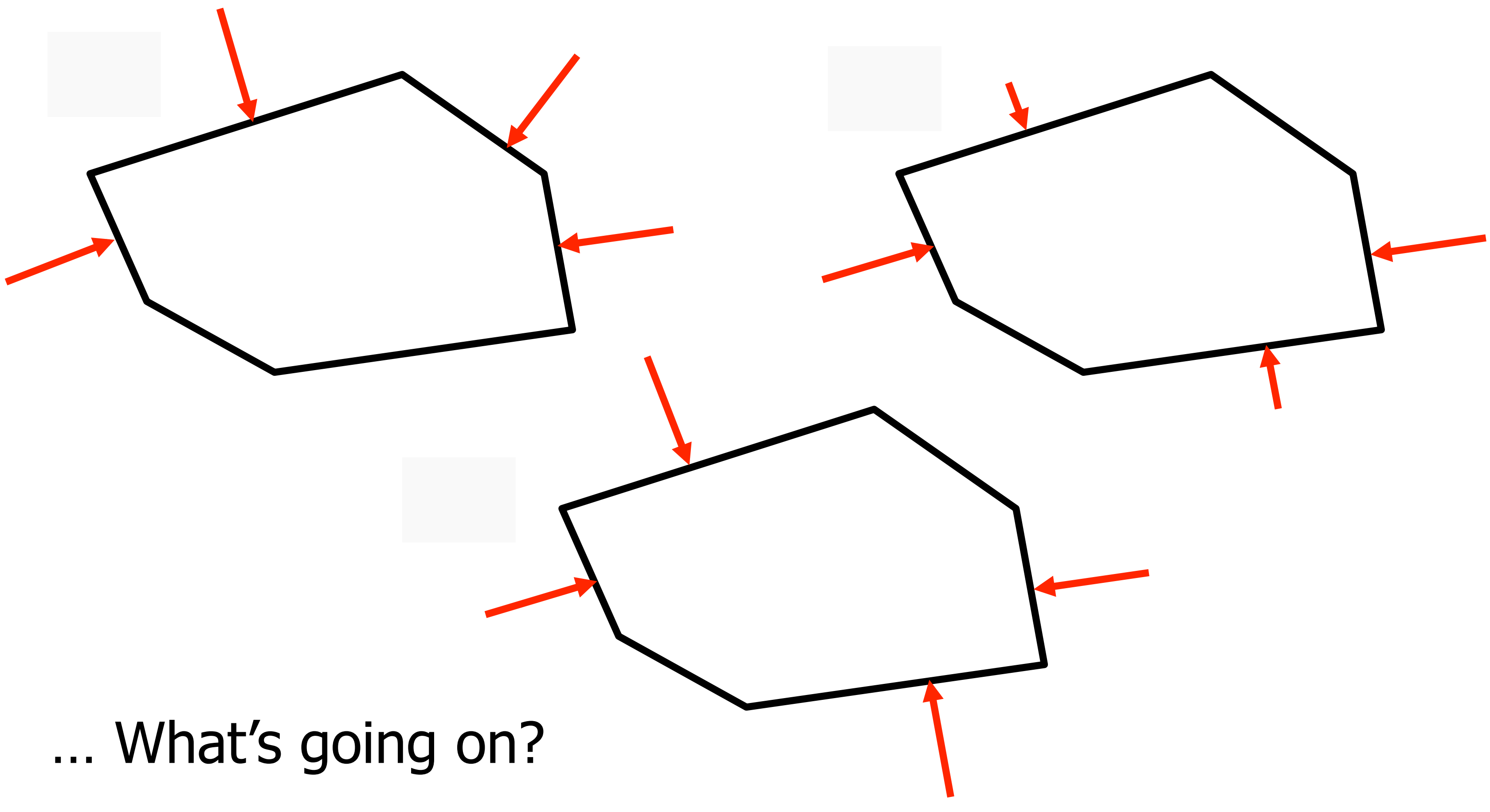
Synthesizing a Force-Direction Grasp

1. Choose admitting a
2. Project onto each contact edge
3. Scale force magnitudes to produce



Torque Closure

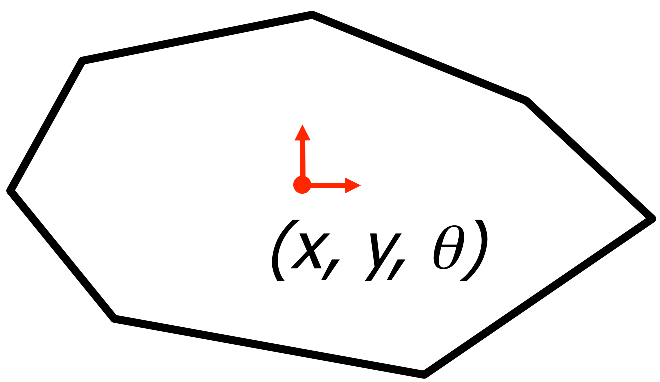
- Under what conditions will a set of point contact forces resist arbitrary planar *rotations*?



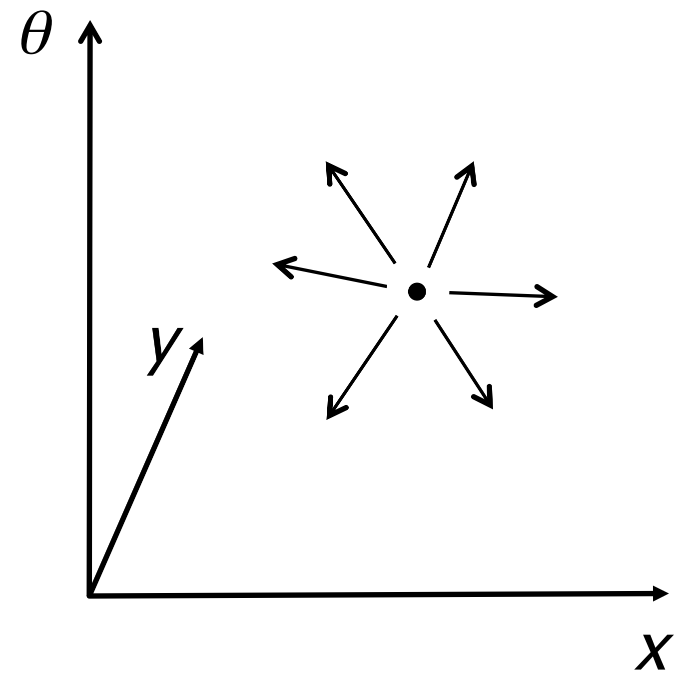
… What's going on?

How many contacts to pin rotation?

- Use analogous DOF argument in c-space
  - First: how many c-space DOFs for object pose?



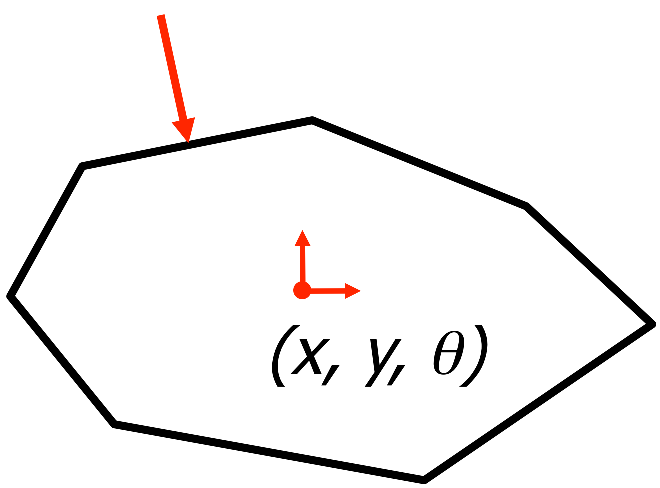
Cartesian space



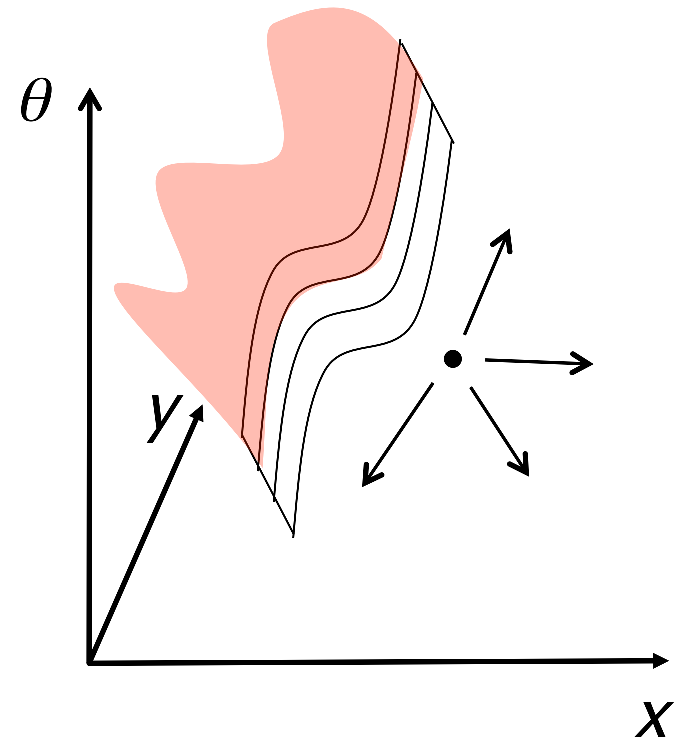
Configuration space

How many contacts to pin rotation?

- Introduce point contact in Cartesian space
  - Implies c-space constraint with 2D manifold boundary



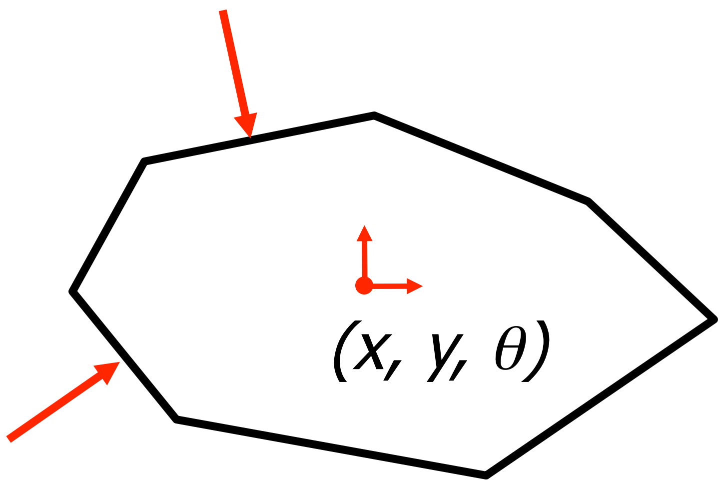
Cartesian space



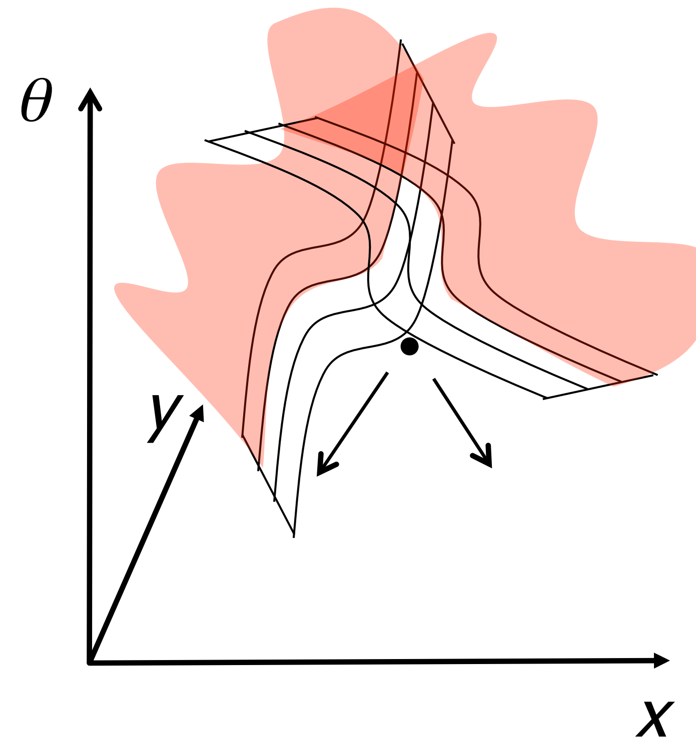
Configuration space

How many contacts to pin rotation?

- Introduce point contact in Cartesian space
  - Implies c-space constraint with 2D manifold boundary



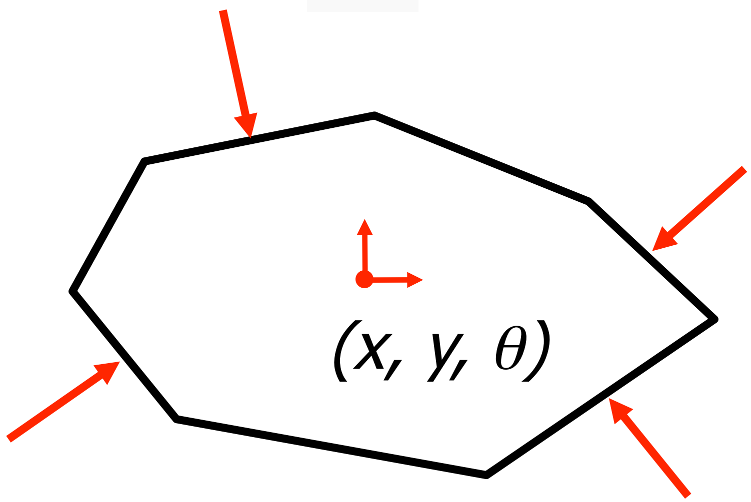
Cartesian space



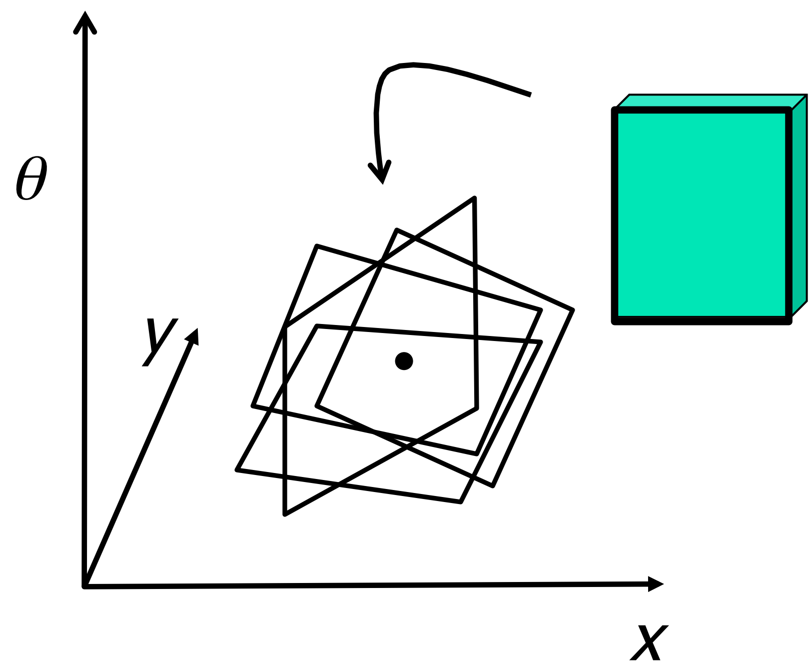
Configuration space

How many contacts to pin rotation?

- Locally, each constraint has a planar boundary
  - … So, how many *halfspaces* needed to pin point?



Cartesian space

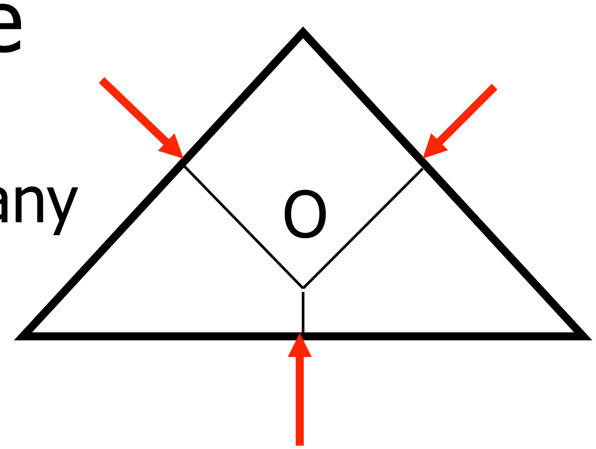


Configuration space

Grasp Analysis (no friction)

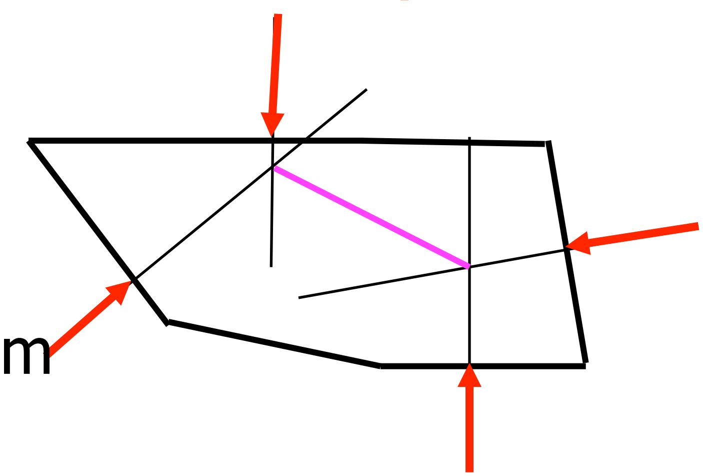
- Force-direction closure

  Translate forces to O;
  they compose to generate any
  desired resultant force



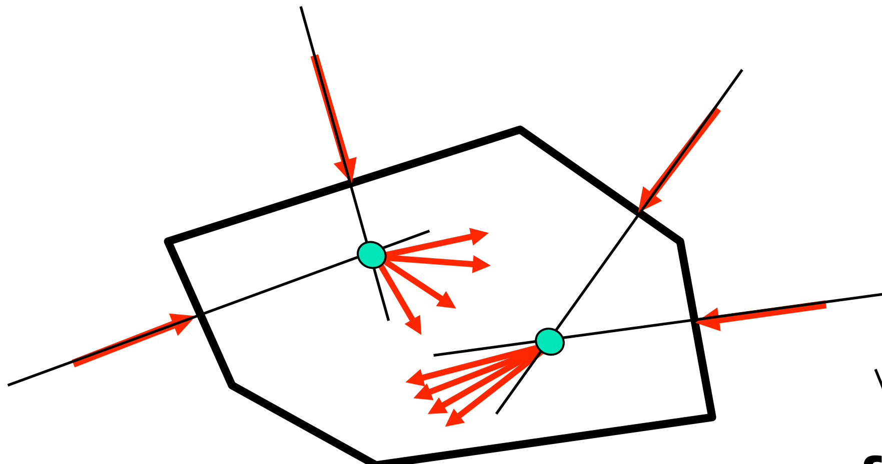
- Torque closure

Translate forces to intersection
Points; they can be adjusted to
point at each other and away from
each other to generate torque

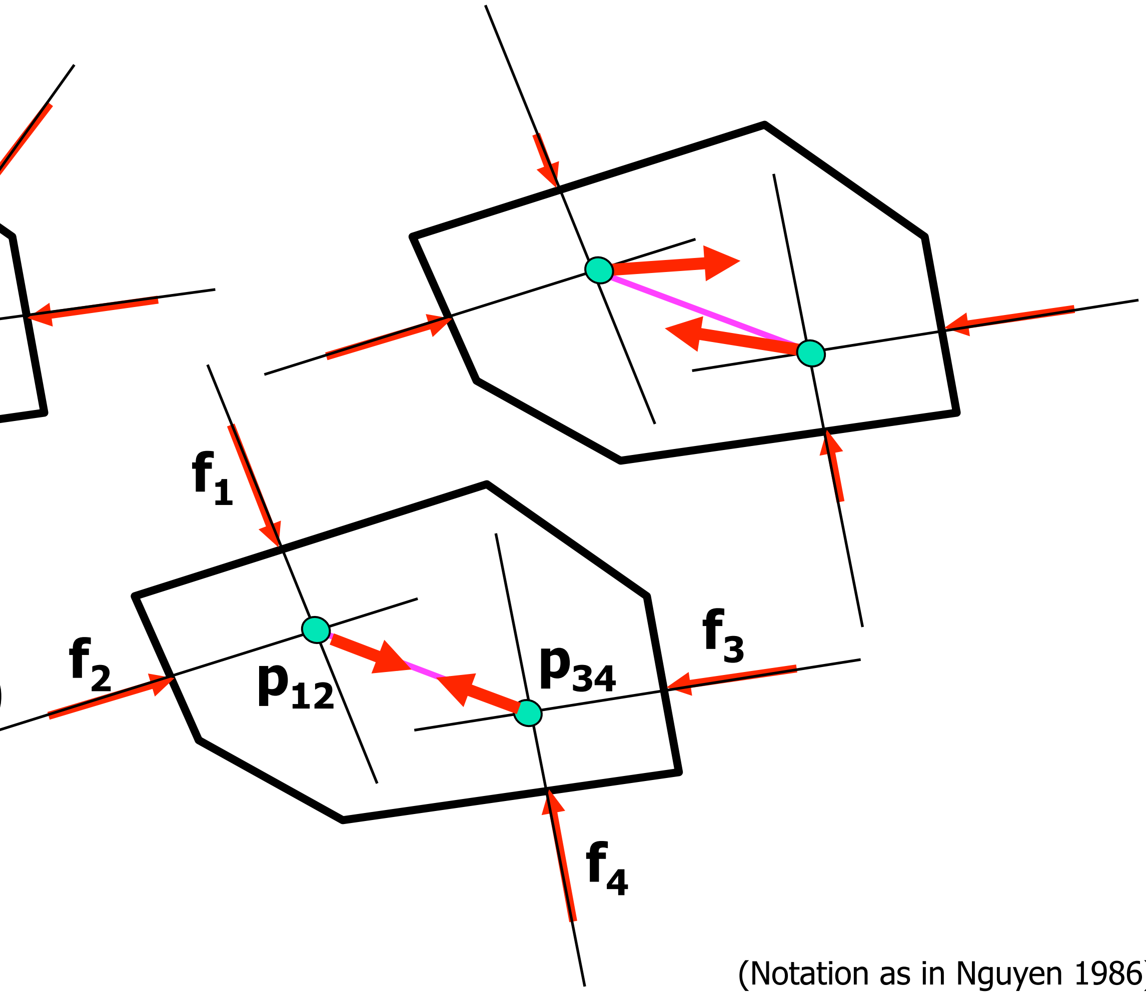


Geometric Conditions for Torque Closure

- Each normal cone must contain the other's apex
- Pairwise effective forces must cancel each other



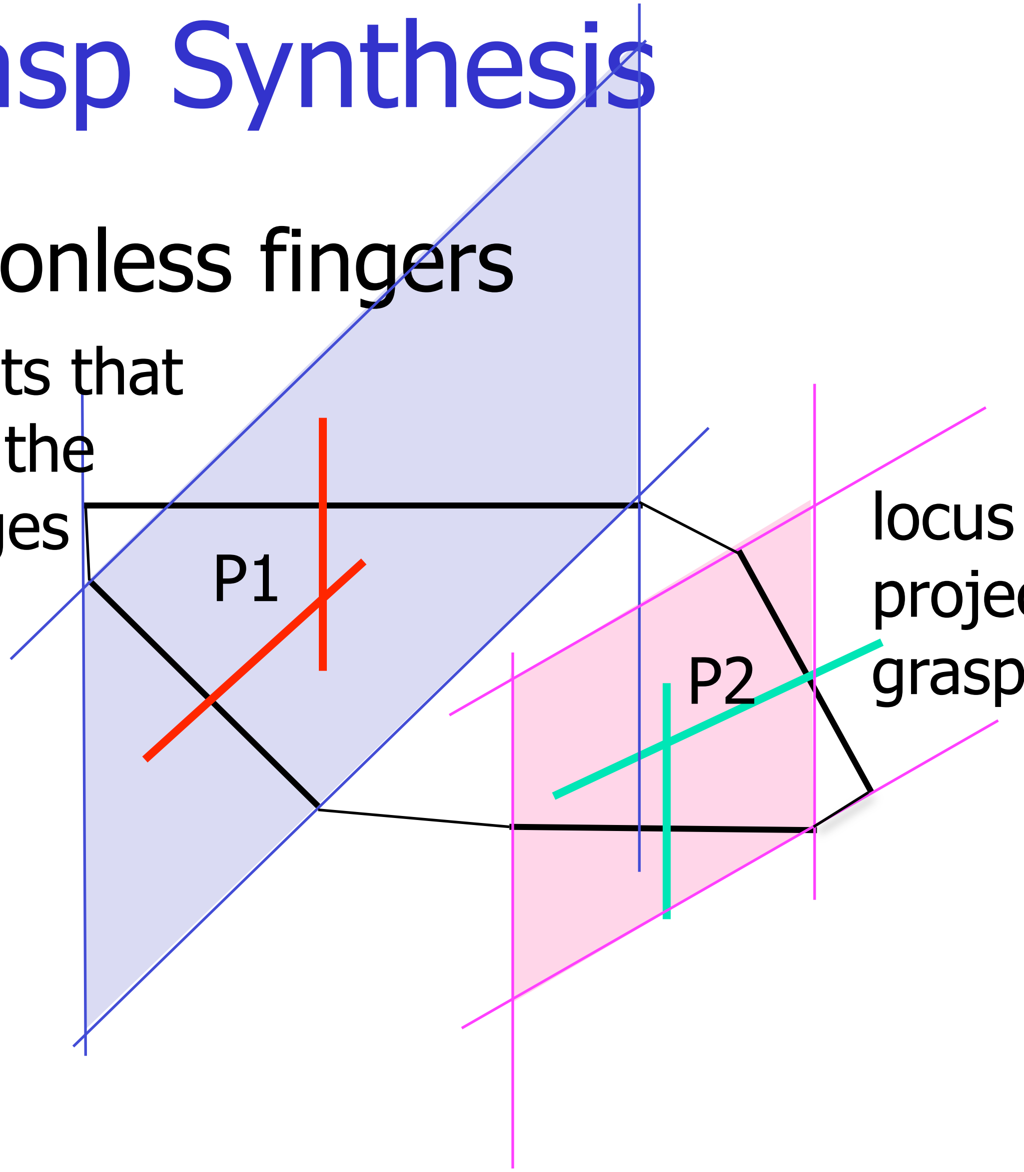
Algebraic condition? For force vectors $\mathbf{f_1}$, $\mathbf{f_2}$, $\mathbf{f_3}$, $\mathbf{f_4}$, there must exist $\alpha, \beta, \gamma, \delta > 0$ s.t.

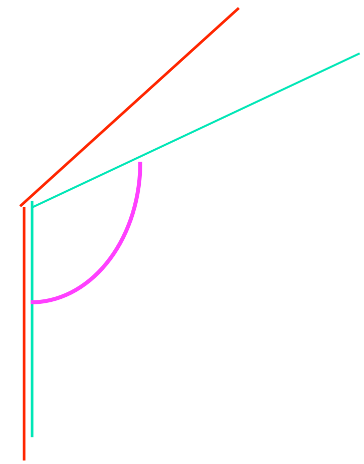


(Notation as in Nguyen 1986)

Grasp Synthesis

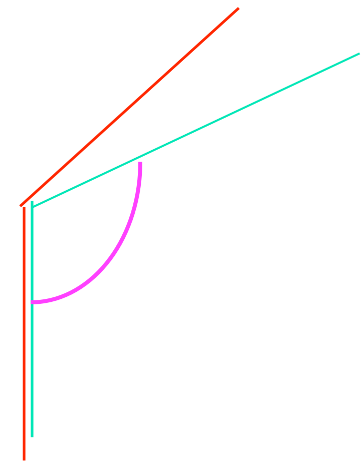
- Frictionless fingers



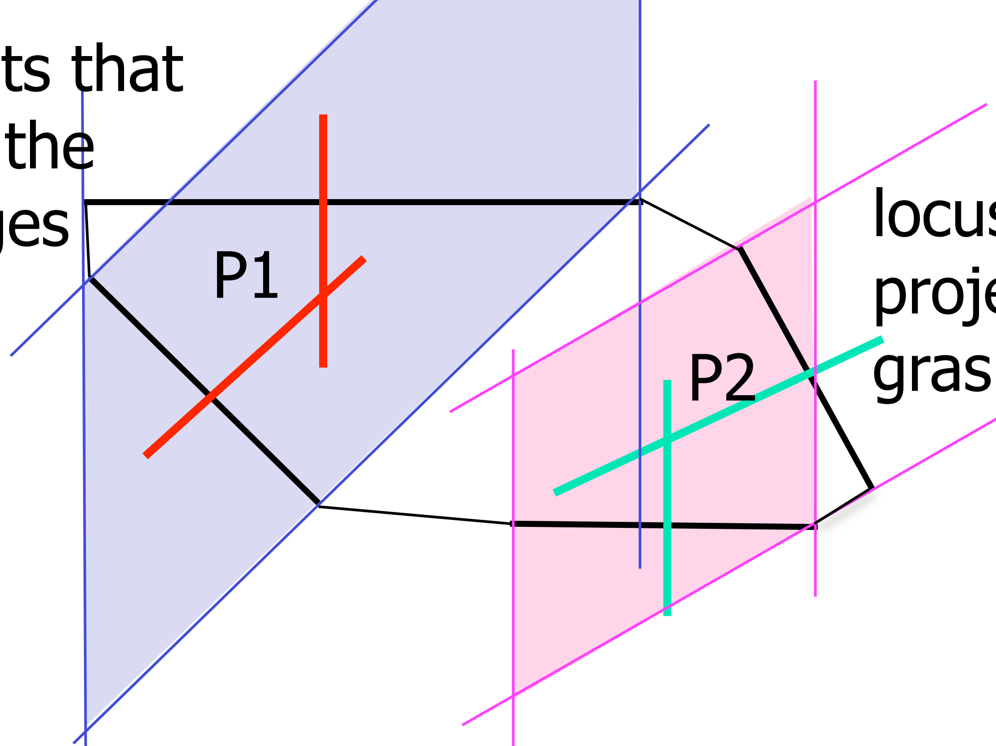


Grasp Synthesis

- Frictionless fingers



locus of points that project onto the grasping edges

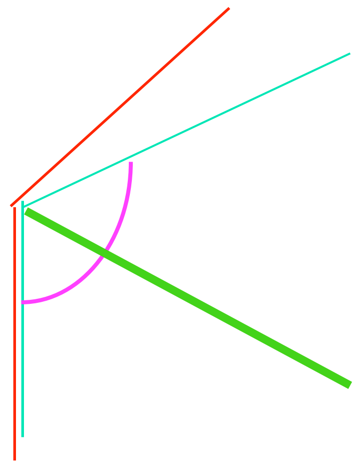


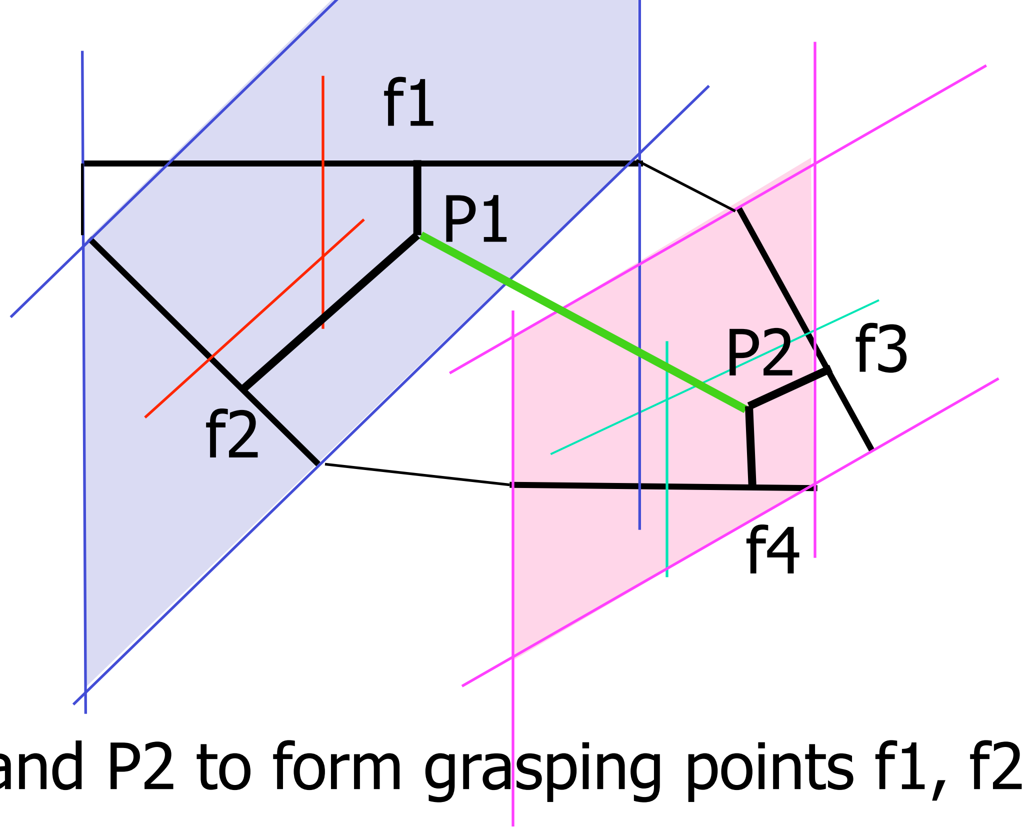
locus of points that project onto the grasping edges

Pick P1 in blue region and P2 in pink region so that the line P1P2 has direction contained in the intersecting normal cones

Grasp Synthesis

- Frictionless fingers



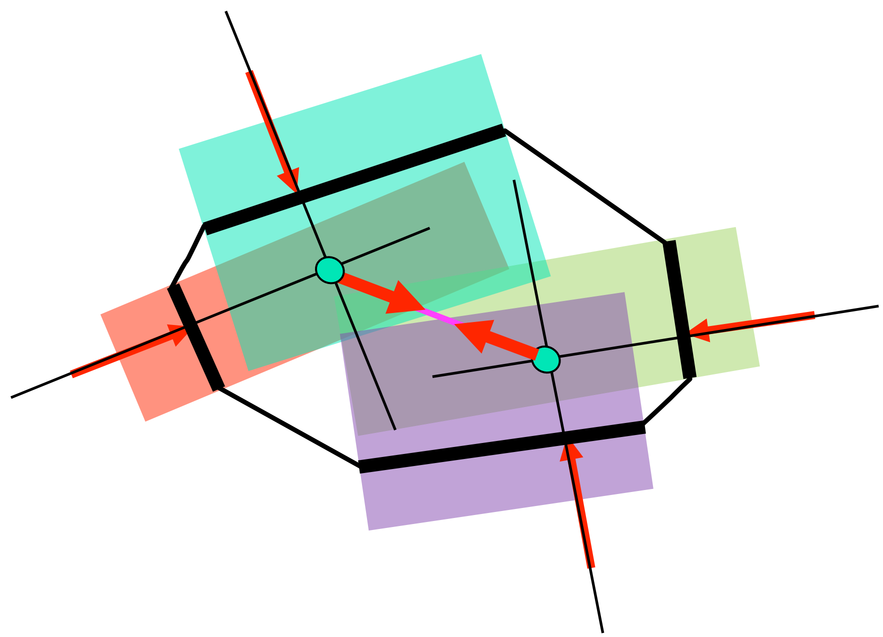


Project P1 and P2 to form grasping points f1, f2, f3, f4

Synthesizing a Torque-Closure Grasp

1. Choose two edge pairs* admitting force centers
2. Choose centers inducing mutual normal cones
3. Project centers to respective edge contact points
4. Scale forces to produce alignment, cancellation

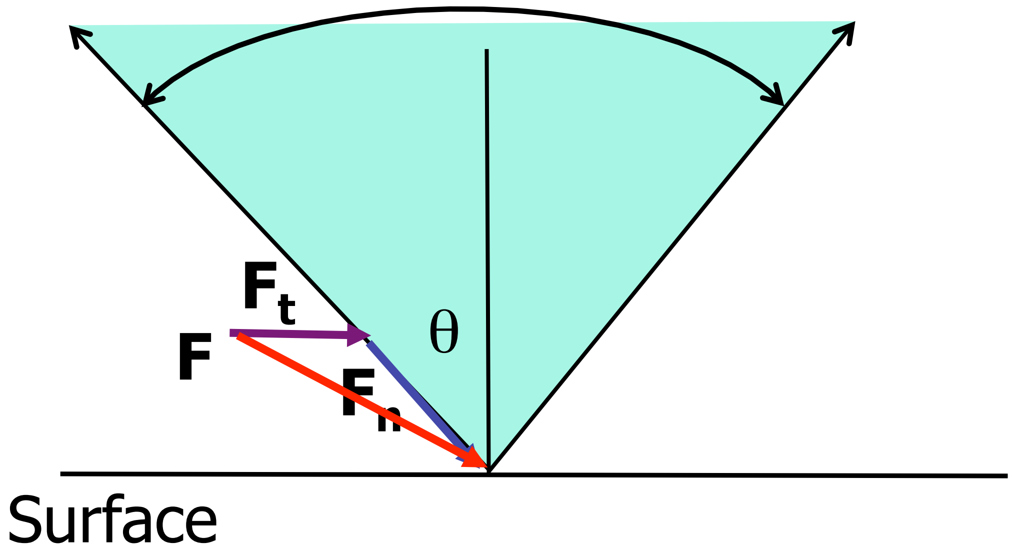
*Edge pairs need not be contiguous



Does rotation closure imply translation closure?

Point Contact with Friction

- Consider a point contact exerting force at some angle θ to the surface normal. What happens?

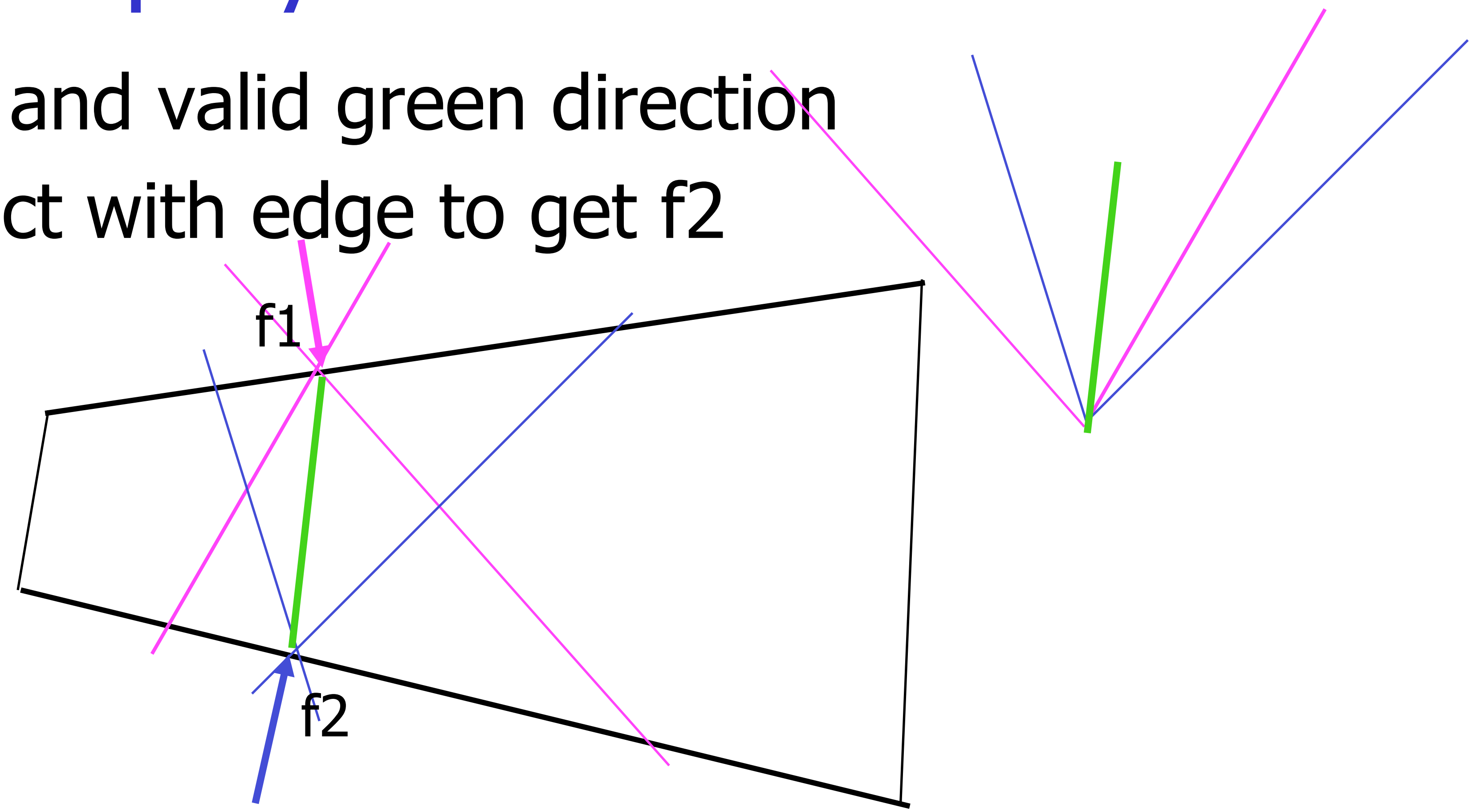


$\theta_{crit} = \tan^{-1} \mu$

- Produces a of force directions

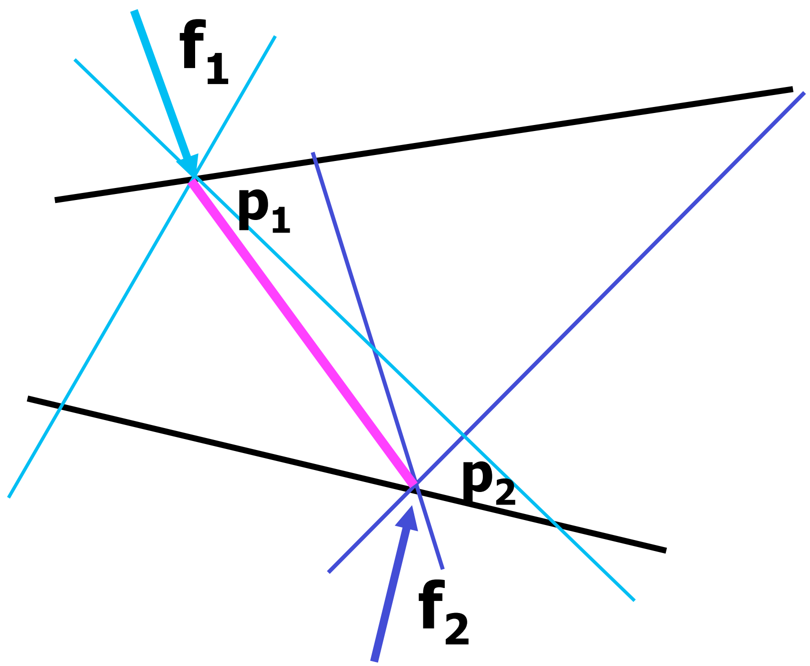
Grasp Synthesis with Friction

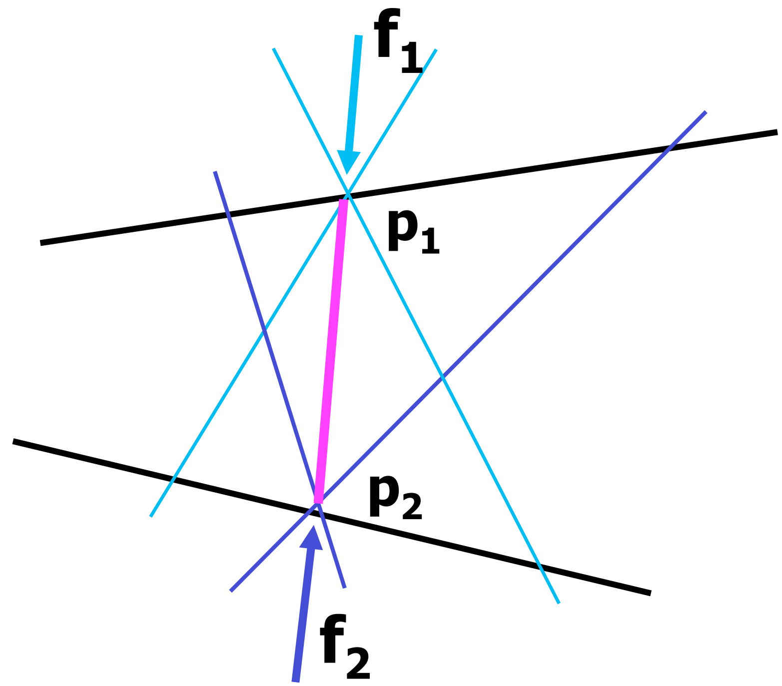
- Pick f1 and valid green direction
- Intersect with edge to get f2



Grasp Analysis With Friction

Consider forces $\mathbf{f_1}$, $\mathbf{f_2}$ at frictional contacts $\mathbf{p_1}$, $\mathbf{p_2}$





When can $\mathbf{f_1}$, $\mathbf{f_2}$ oppose one another without sliding?

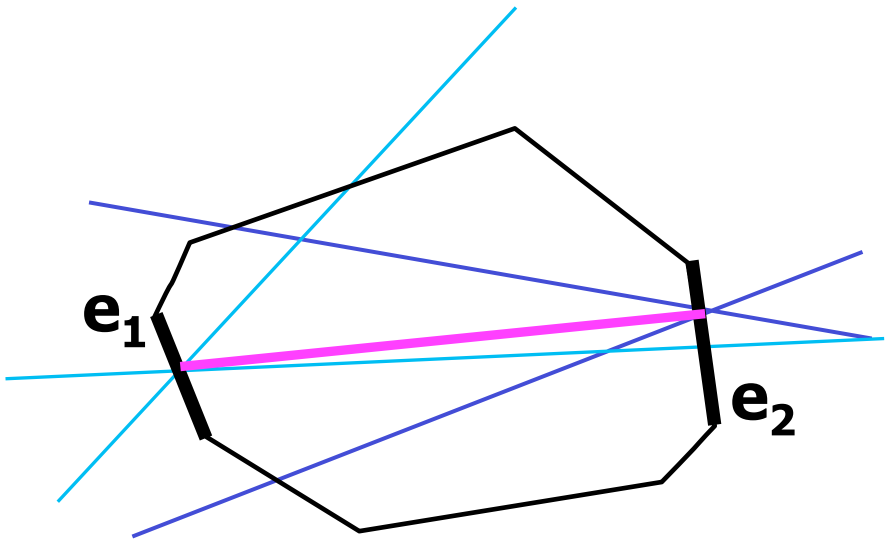
Each force must

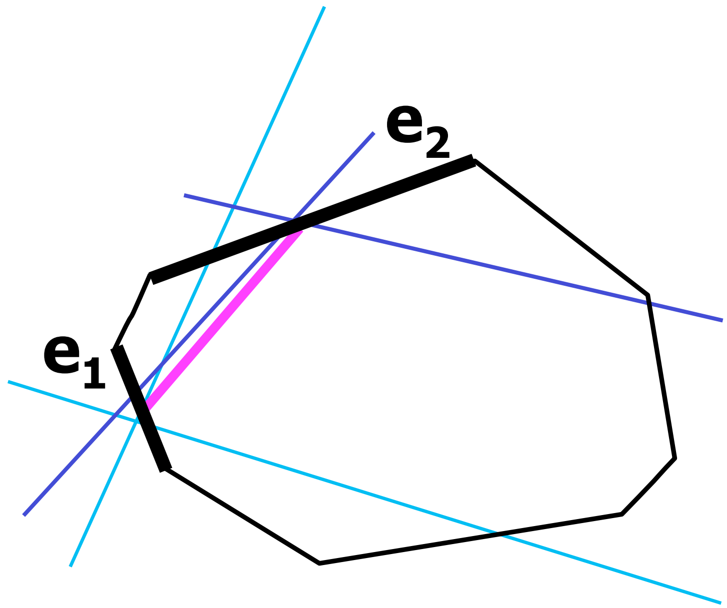
Point $\mathbf{p_1}$ (resp. $\mathbf{p_2}$) must

Grasp Synthesis With Friction

Choose a *compatible* pair of edges $\mathbf{e_1}$, $\mathbf{e_2}$

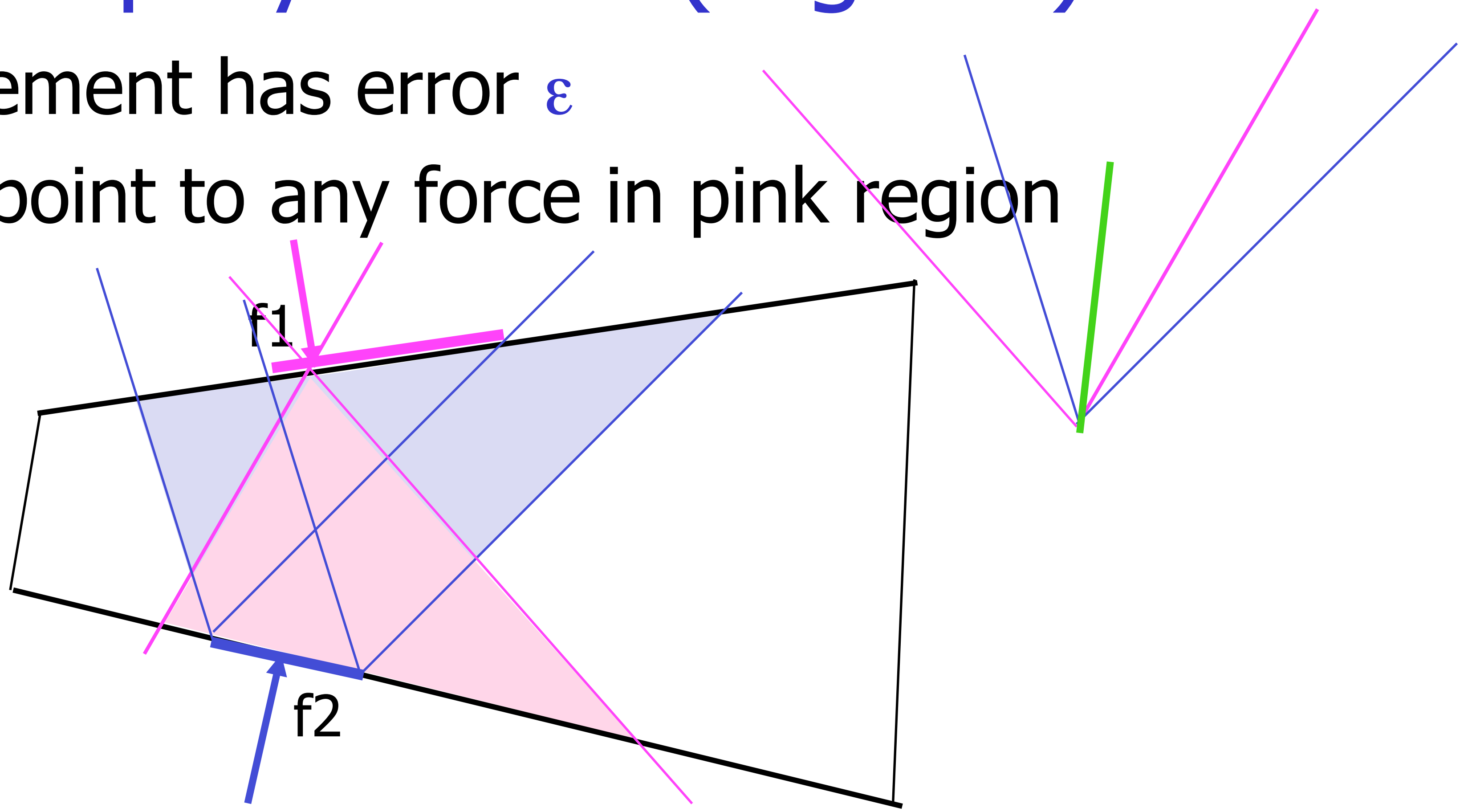
Intuition? Using what data? How to choose?





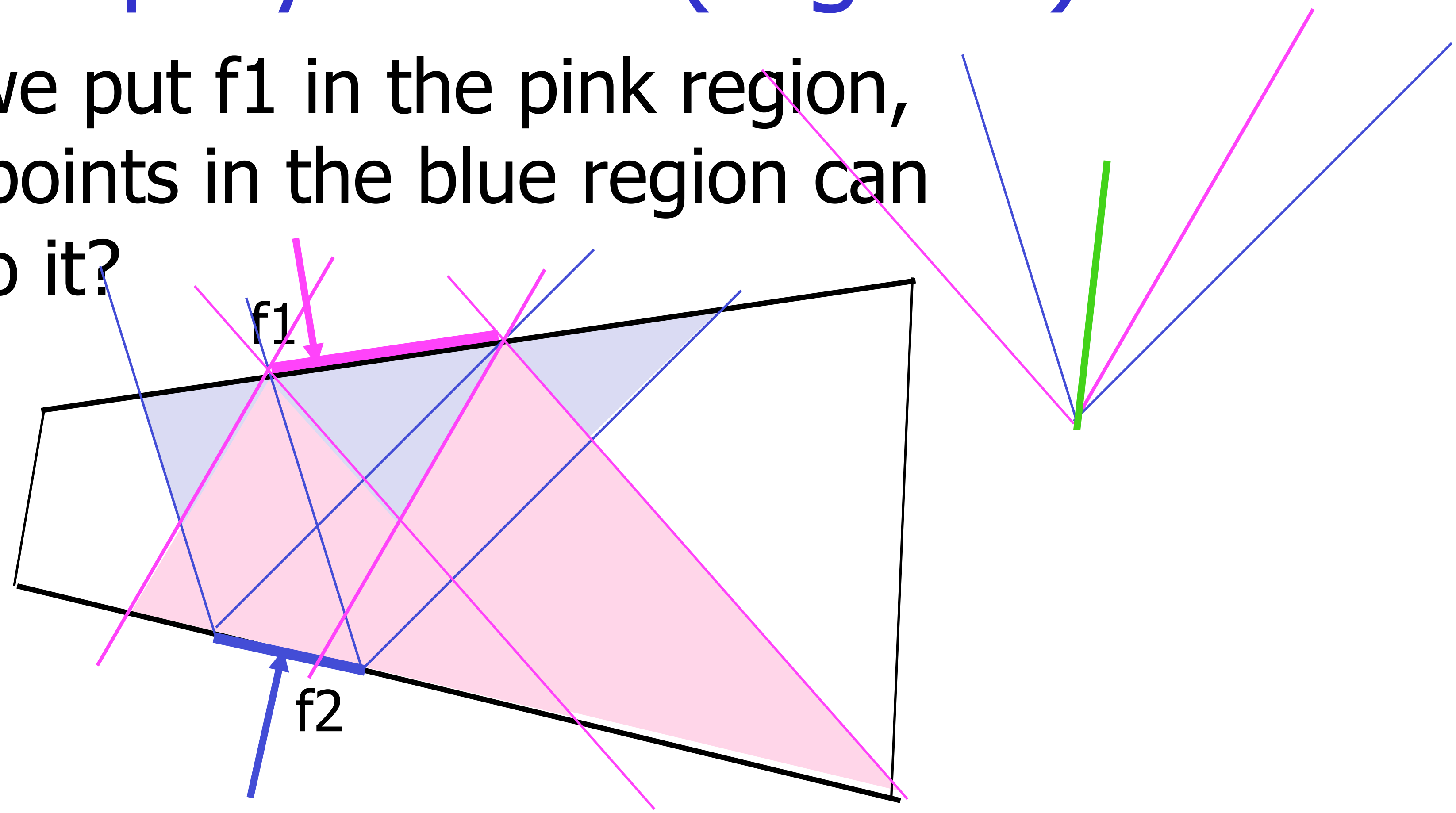
Grasp Synthesis (regions)

- f2 placement has error ε
- f2 can point to any force in pink region



Grasp Synthesis (regions)

- But if we put f1 in the pink region, which points in the blue region can point to it?



Grasp Synthesis (friction)

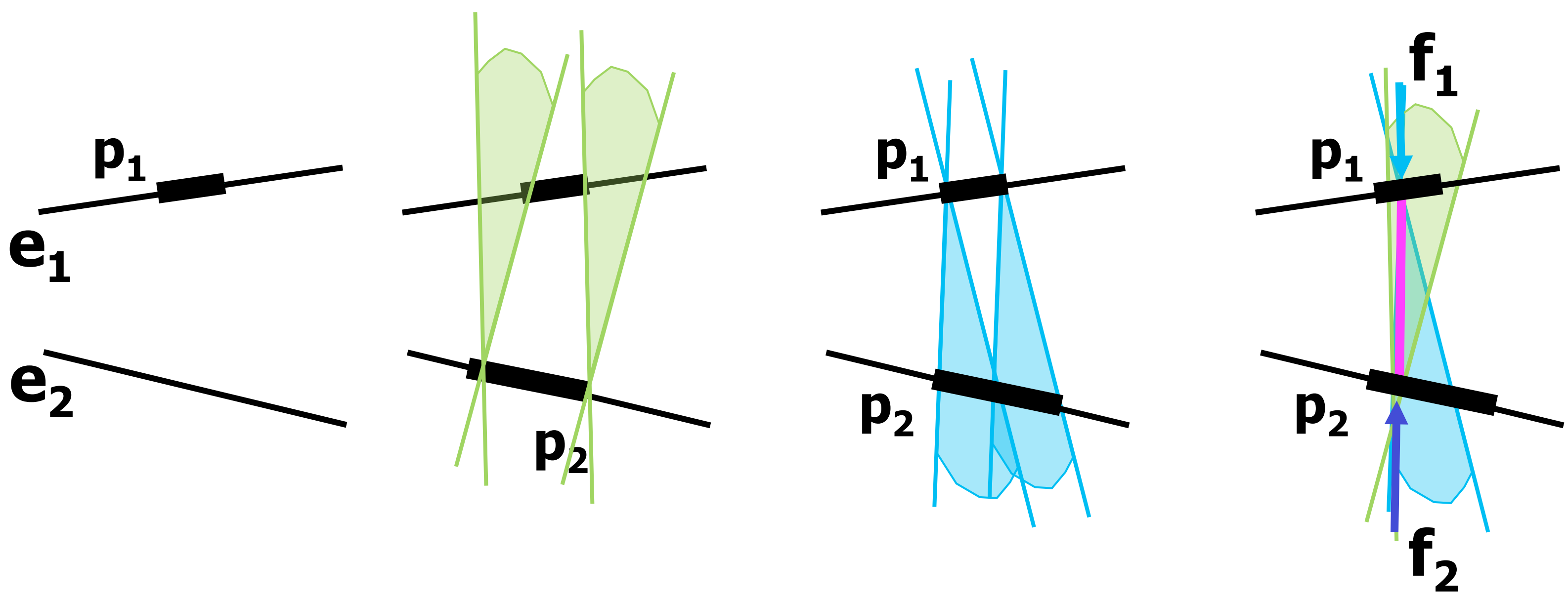
- 2 Finger Forces have to be within friction cones to stick
- 2 Finger Forces have to point at each other
- So…
- We need to find 2 edges with overlapping friction cones

Grasp Synthesis With Friction

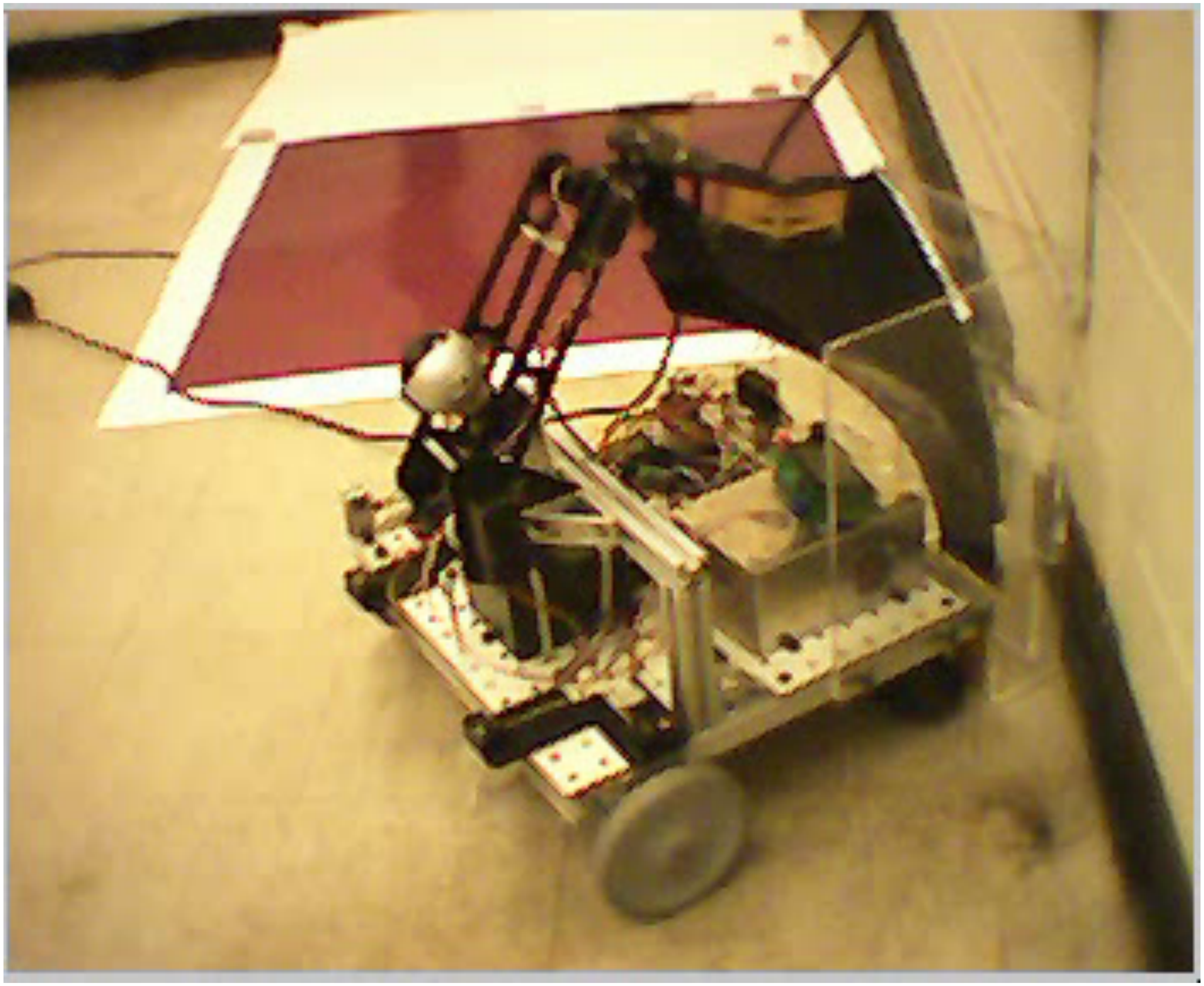
Choose target region for contact point $\mathbf{p_1}$

Determine feasible target region for contact $\mathbf{p_2}$

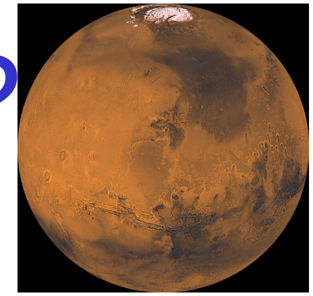
Orient and scale $\mathbf{f_1}$, $\mathbf{f_2}$ so as to cancel along $\overline{\mathbf{p_1 p_2}}$

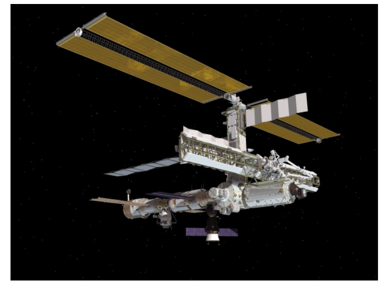


Example: 6.141 robot

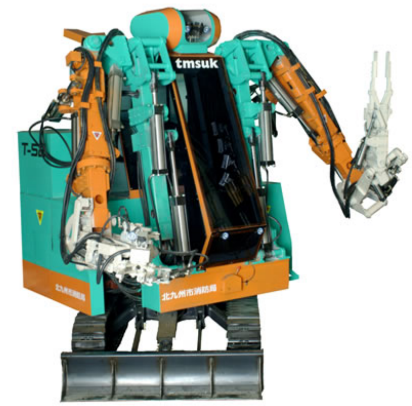


What is Robot Manipulation?

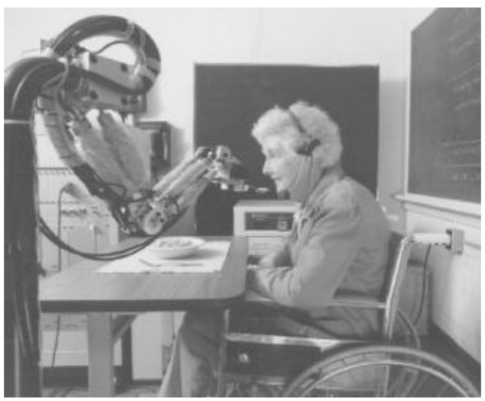




Space - in-orbit, repair and maintenance, planetary exploration anthropomorphic design facilitates collaboration with humans



Home - basic science - manufacturing, logistics, automated warehousing and distribution, computational models of cognitive systems, learning, human interfaces



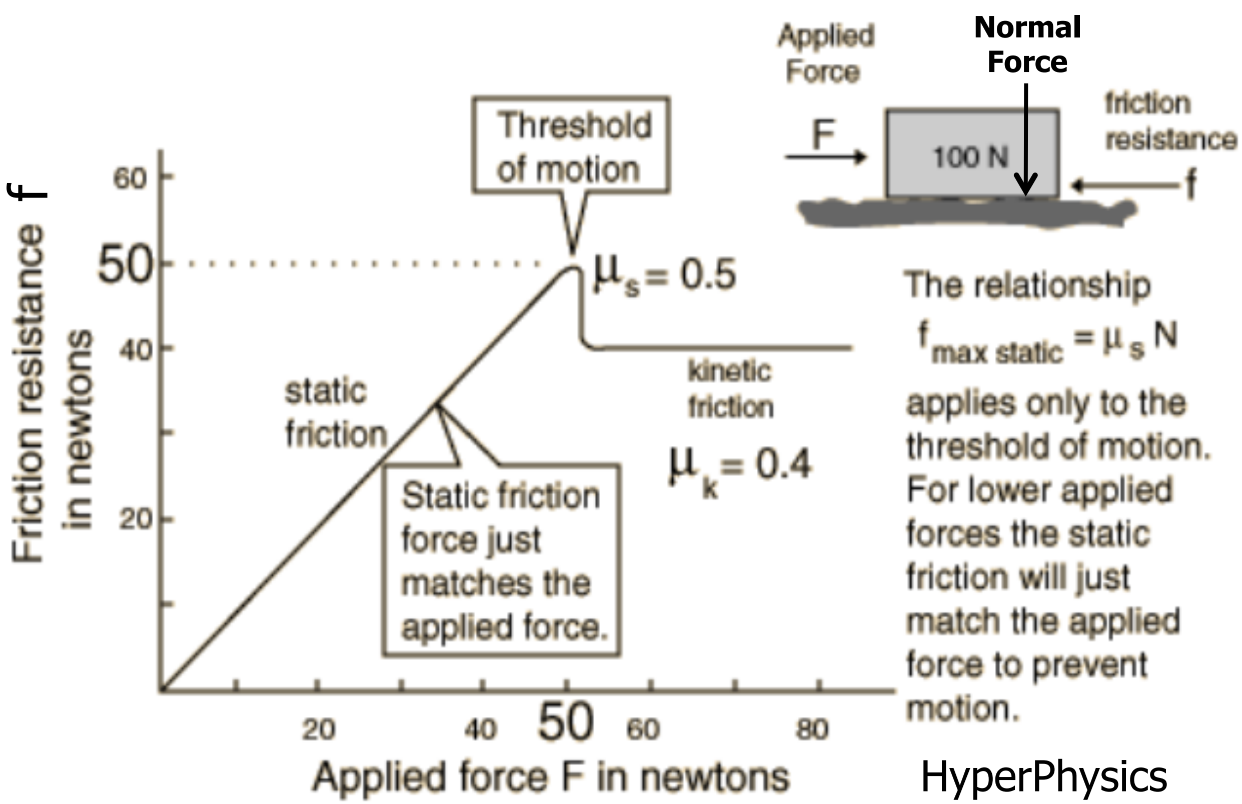
Assistive - clinical applications, "aging-in-place," physical and cognitive prosthetics in assisted-living facilities

Military - supply chain and logistics support, re-fueling, bomb disposal

Kinetic and Static Friction ("Stiction")

$F_f <= \mu_s * F_n$ (at rest): coefficient of static friction μ_s

$F_f <= \mu_k * F_n$ (moving): coefficient of kinetic friction μ_k

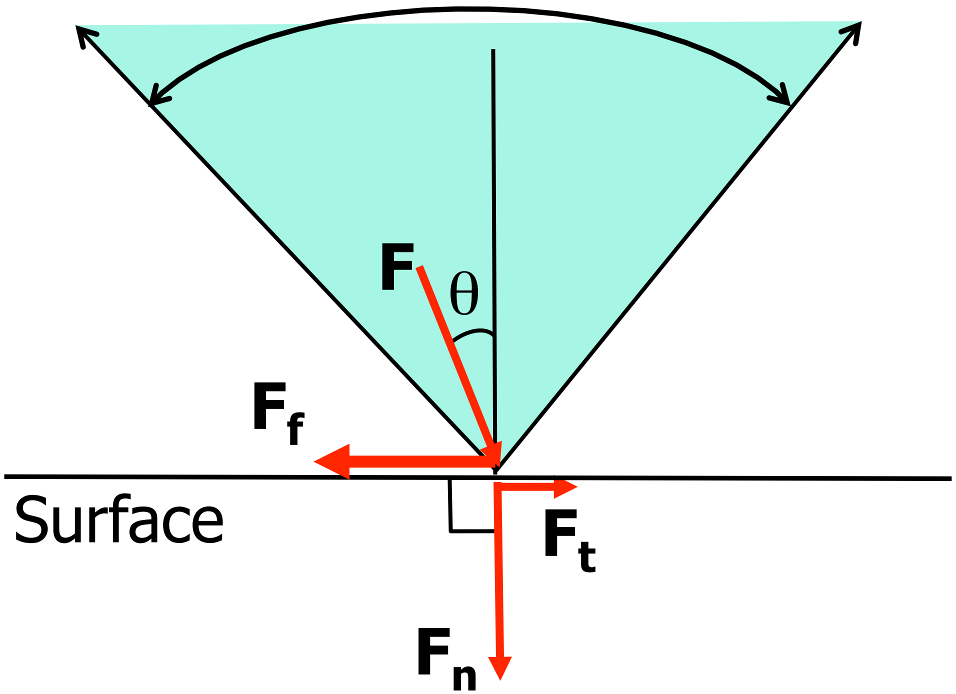


HyperPhysics

(Stiction makes things difficult both for humans and robots. Why?)

Point Contact with Friction

- Consider a point contact exerting force at some angle θ to the surface normal. What happens?



For contact at rest,

$|\mathbf{F_t}| < |\mathbf{F_f}| = \mu\, |\mathbf{F_n}|$

At critical angle θ_{crit},

$|\mathbf{F_t}| =$

Substituting gives

$|\mathbf{F}| \sin \theta_{crit} =$

Which yields

$\mu =$

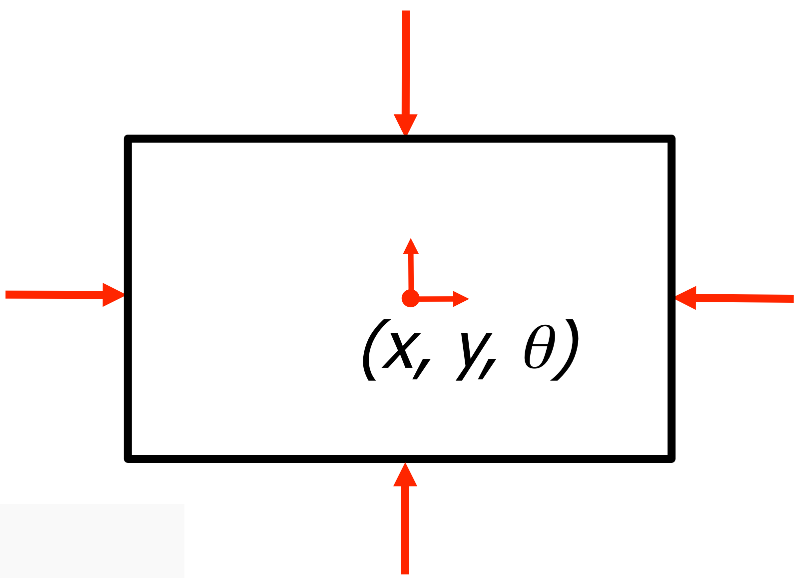
So that

$\theta_{crit} =$

- Produces a of force directions

Are There Degeneracies?

- Polygon with sides not in general position...
- But what about circles ?



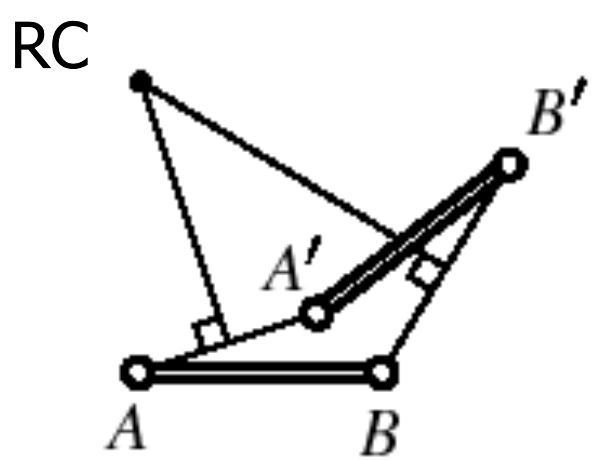
Cartesian space

Cartesian space

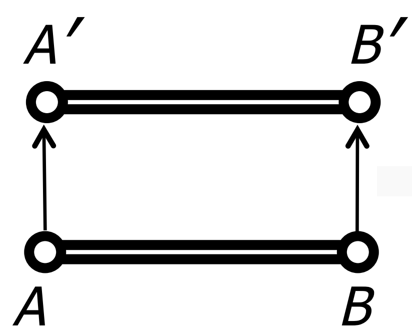
- For polyhedra in 3D: need
  - Frictionless contacts cannot pin

Rotation Center (RC)

- Consider *finite* planar displacement of rigid object
  - Some point in the plane is left fixed by displacement
  - This point is called the "rotation center" (RC)
- What if the displacement is a pure translation?
  - Where is the RC?

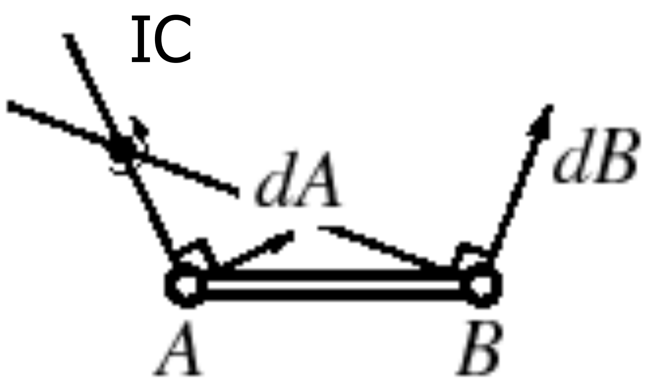


Mason, MoRM

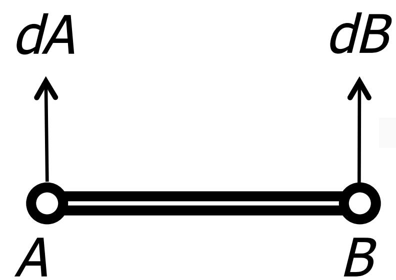


Instantaneous Center (IC):

- Consider a *differential* displacement (i.e. velocity)
  - Displacement still has a fixed point; where is it?
- What if the displacement is a pure translation?
  - Where can the IC lie?

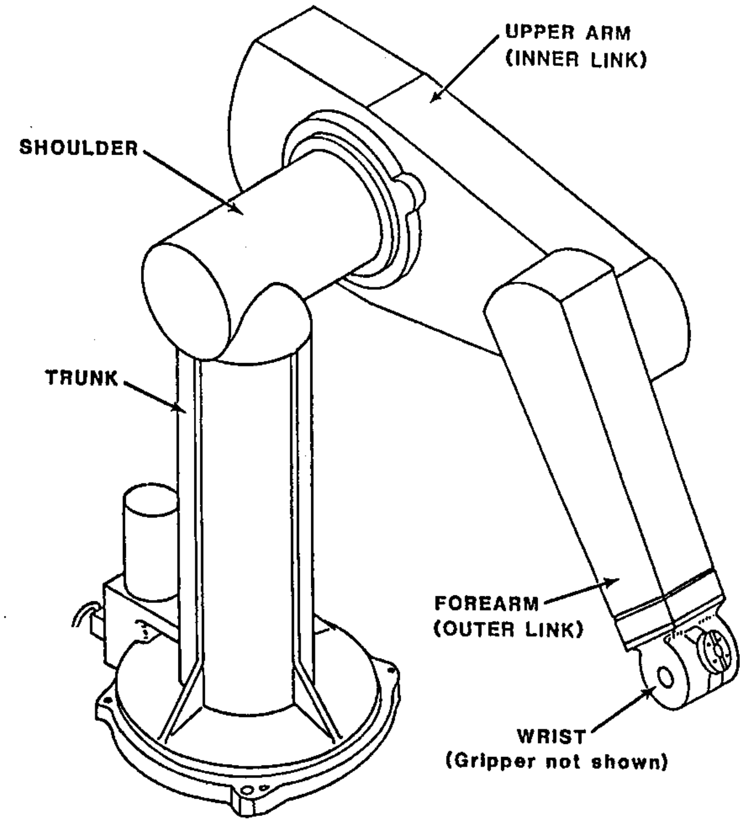


Mason, MoRM



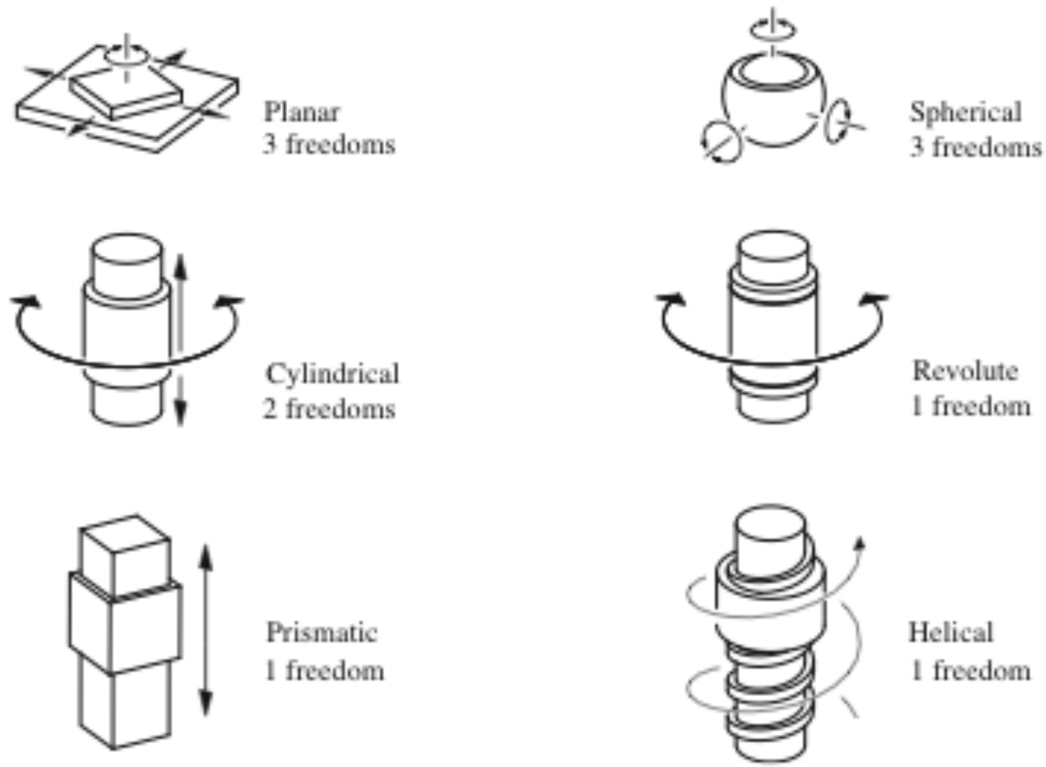
Arm Control to Reach

- Mechanism design
- Forward kinematics
- Inverse kinematics



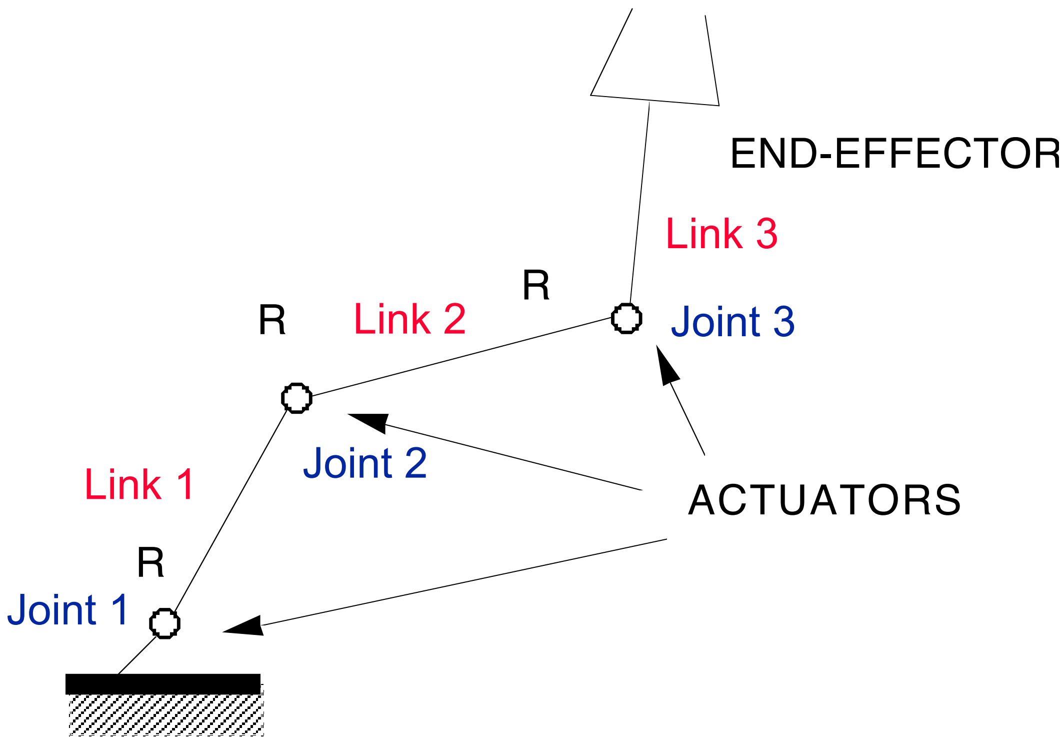
Kinematic Mechanisms

Link: rigid body
Joint: constraint
on two links
Kinematic mechanism:
links and joints



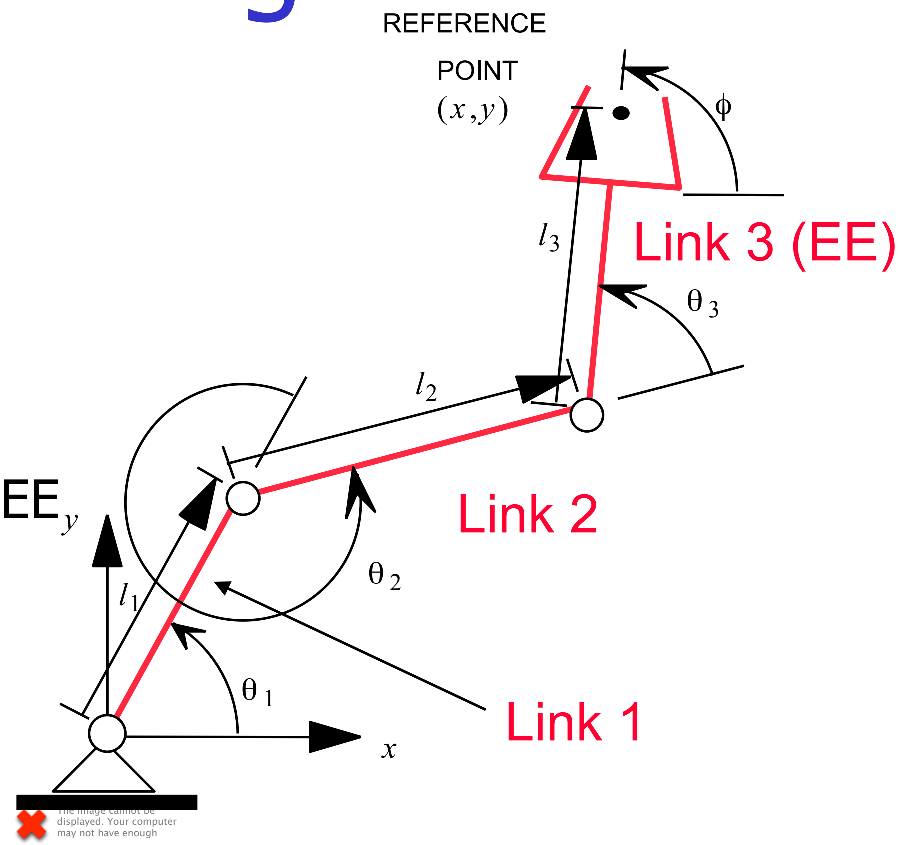
The Planar 3-R manipulator

- Planar kinematic chain
- All joints are revolute



Kinematic modeling

- Link
- Actuated joint
- End effector (EE)
  - Reference point on EE



- Joint coordinates

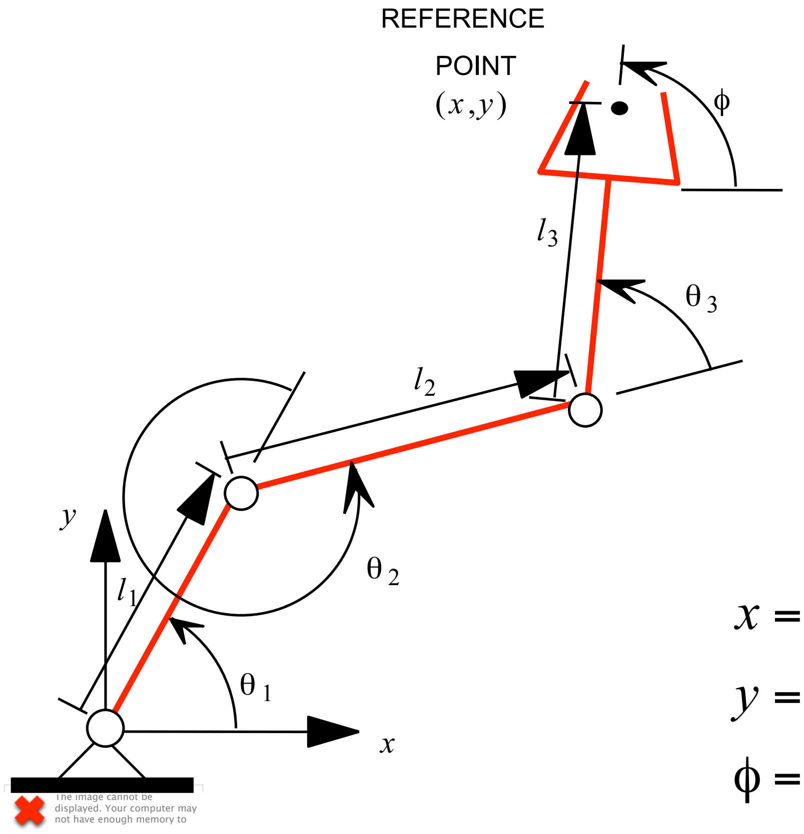
  $\theta_1, \theta_2, \theta_3$
- End effector coordinates

  x, y, ϕ
- Link lengths (l_i)

Kinematic transformations

- Direct kinematics
  - Joint coordinates to end effector coordinates
    - Sensors are located at the joints. DK algorithm is used to figure out where the robot is in 3-D space.
    - Robot "thinks" in joint coordinates. Programmer/ engineer thinks in "world coordinates" or end effector coordinates.
- Inverse kinematics
  - End effector coordinates to joint coordinates
    - Given a desired position and orientation of the EE, we want to be able to get the robot to move to the desired goal. IK algorithm used to obtain the joint coordinates.
    - Essential for control.

Direct kinematics



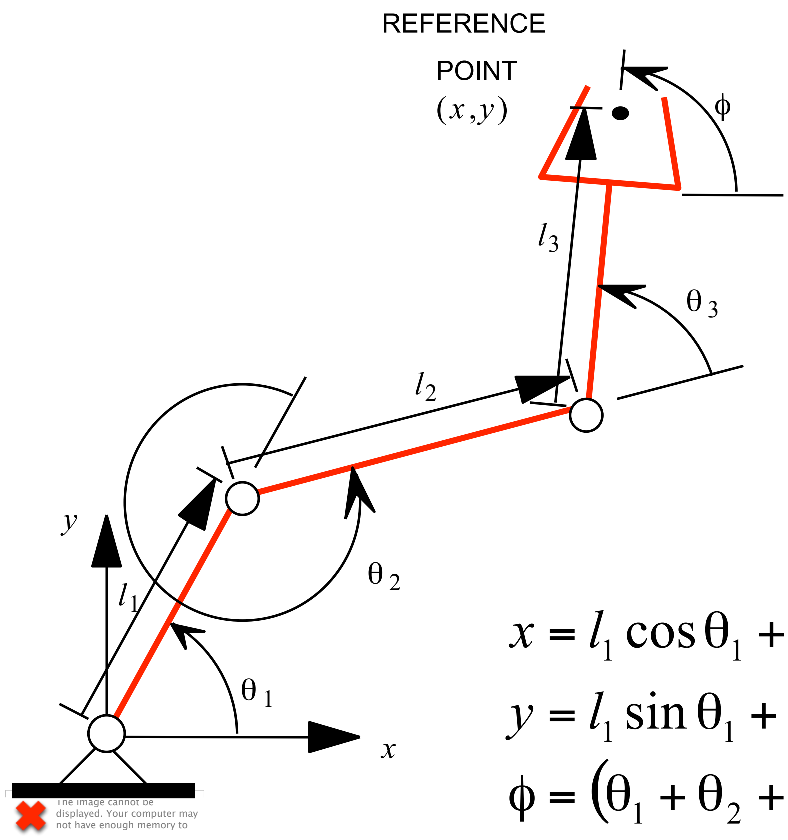
- Transform joint coordinates to end effector coordinates

$$x = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)$$

$$y = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3)$$

$$\phi = (\theta_1 + \theta_2 + \theta_3)$$

Inverse kinematics

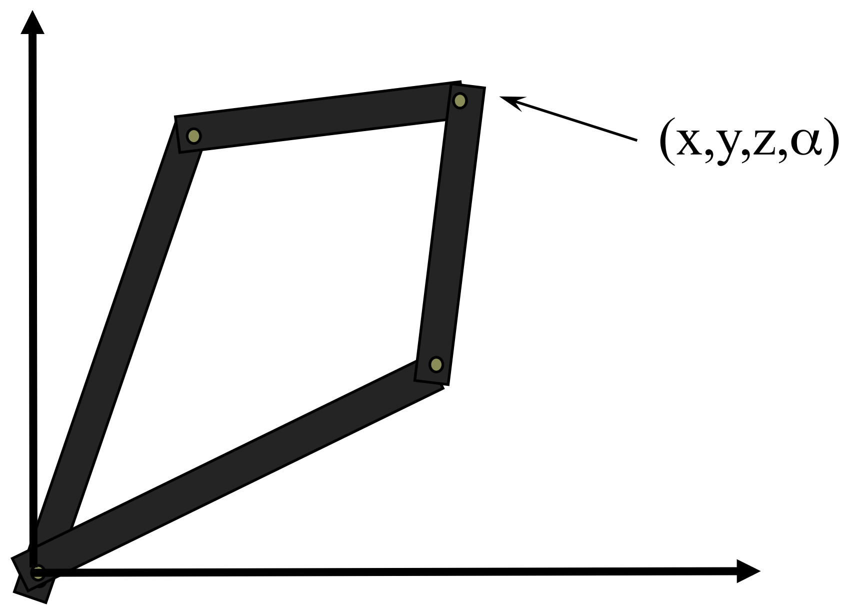


- Transform end effector coordinates to joint coordinates

$$x = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)$$
$$y = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3)$$
$$\phi = (\theta_1 + \theta_2 + \theta_3)$$

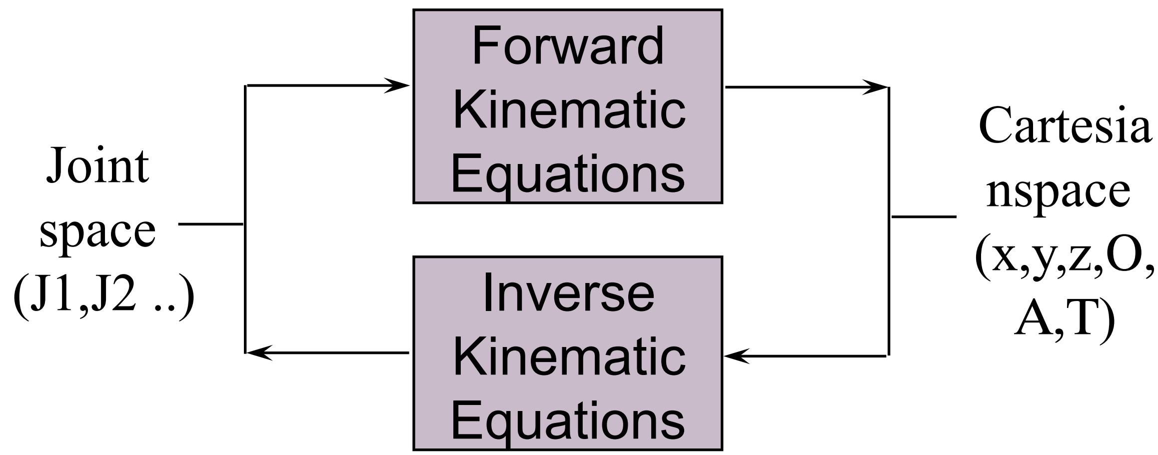
Given x, y, ϕ, solve for θ_1, θ_2, θ_3

Inverse kinematics has multiple solutions



Which is the correct robot pose ?

Kinematics Summary

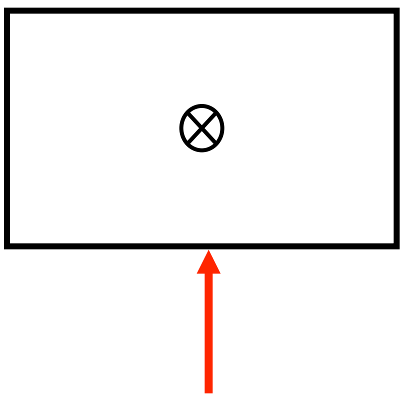


Robot kinematic calculations deal with the relationship between joint positions and an external fixed Cartesian coordinate frame.

Dynamics, force, momentum etc. are not considered.

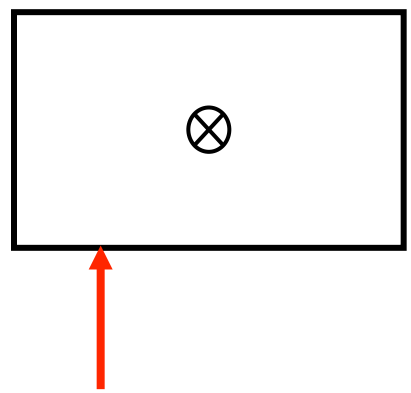
Pushing

- Straight-line motion



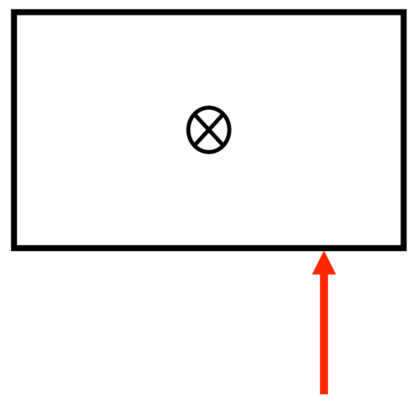
Pushing

- Clockwise rotation



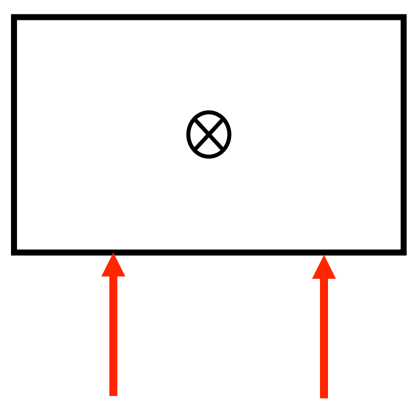
Pushing

- Counter-clockwise rotation



Pushing

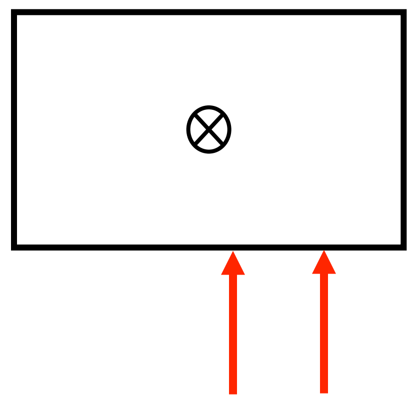
- Robust translation



What if we do not know where the center of mass is?

Pushing

- Robust translation

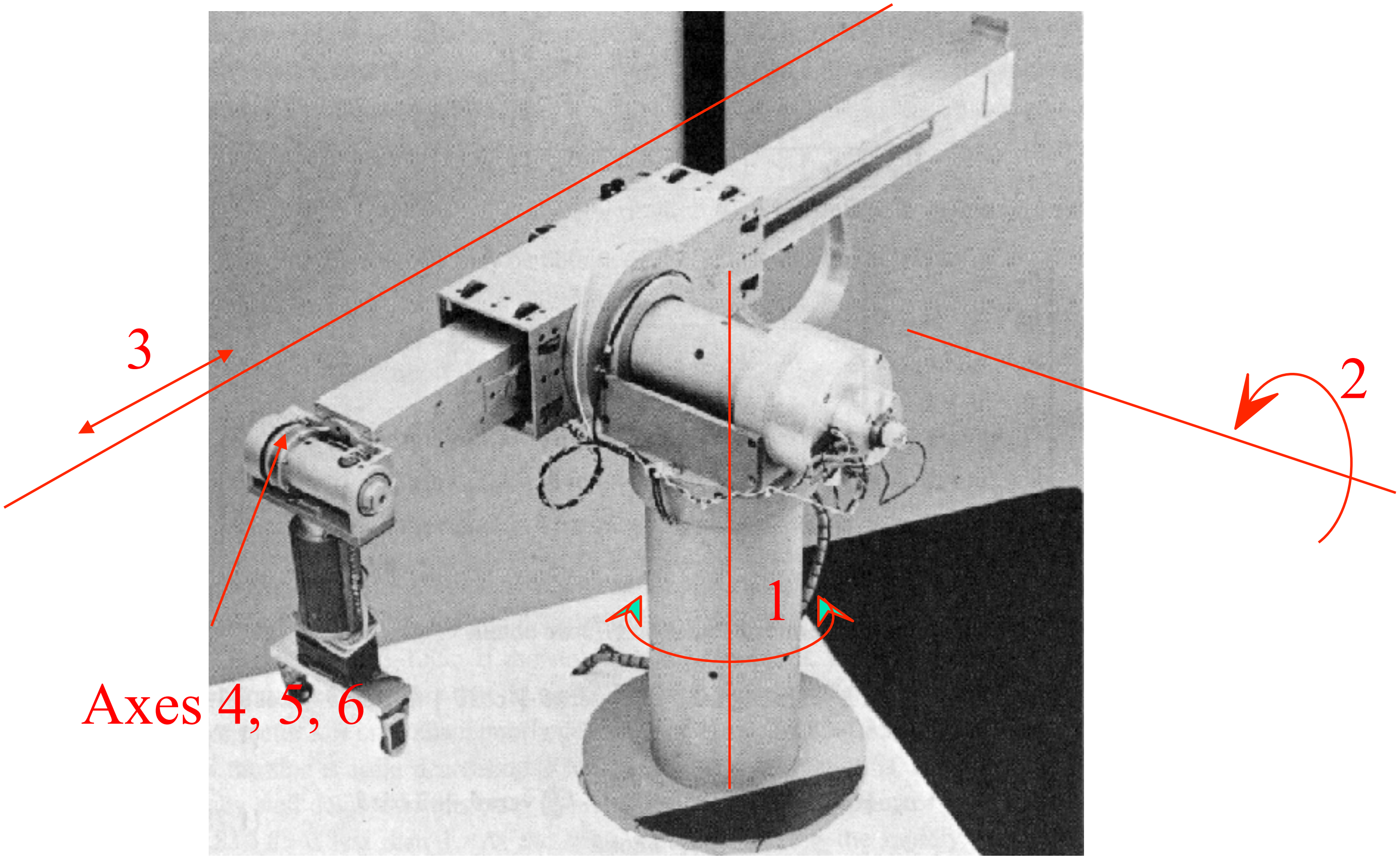


Push and sense: if clockwise rotation, move right
if counterclockwise rotation move left

Grasping and manipulation summary

- Reaching: forward and inverse kinematics
- Grasping: analysis and synthesis of closure grasps
- Manipulation: prehensile and non-prehensile

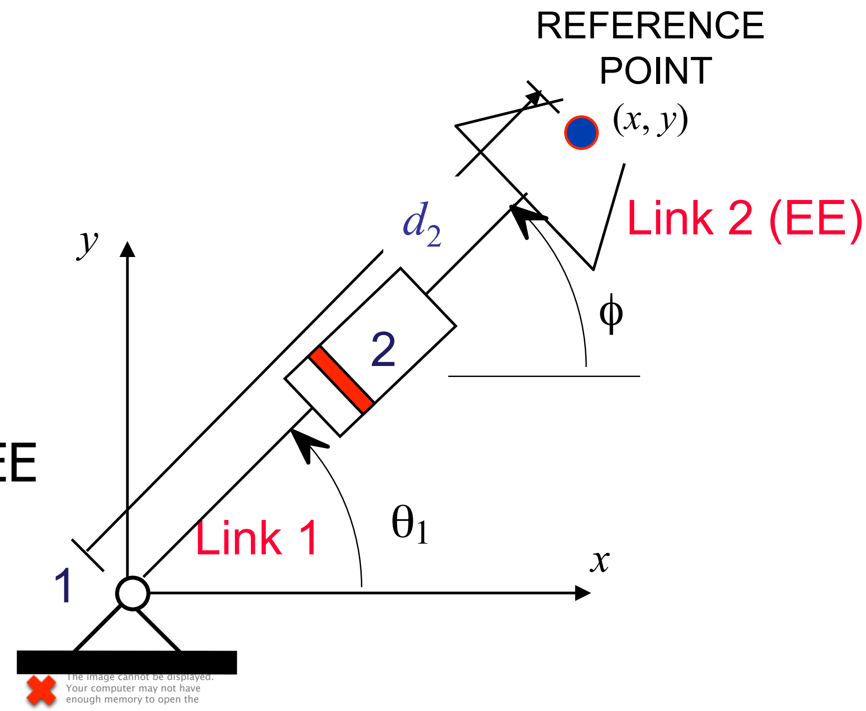
Another Example



Research prototype (BARM, YARM) developed by Stanford University (1960's)

Kinematic modeling

- Link
- Actuated joint
- End effector (EE)
  - Reference point on EE



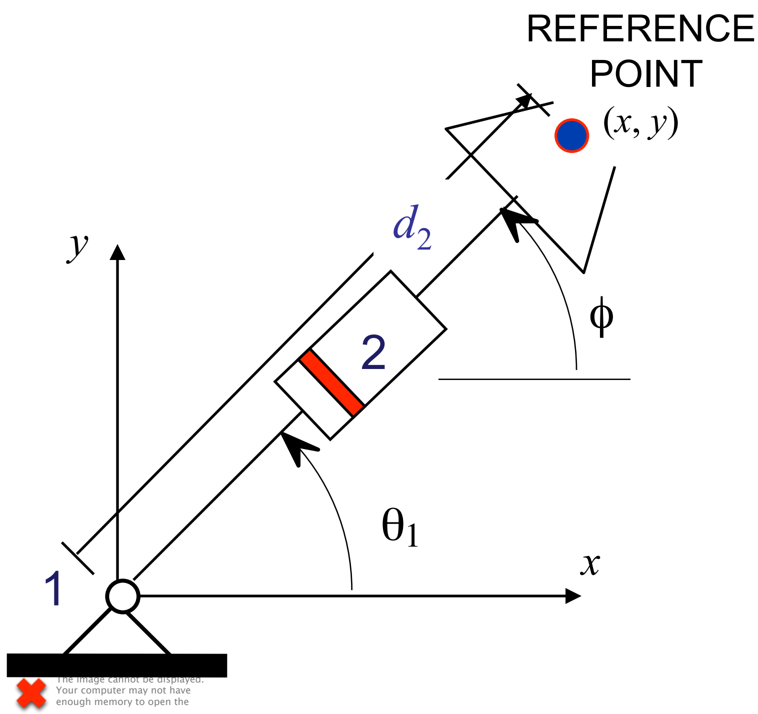
- Joint coordinates

  θ_1, d_2
- End effector coordinates

  x, y, ϕ

RP manipulator

Inverse kinematics



Transform end effector coordinates to joint coordinates

$$x = d_2 \cos\theta_1$$

$$y = d_2 \sin\theta_1$$

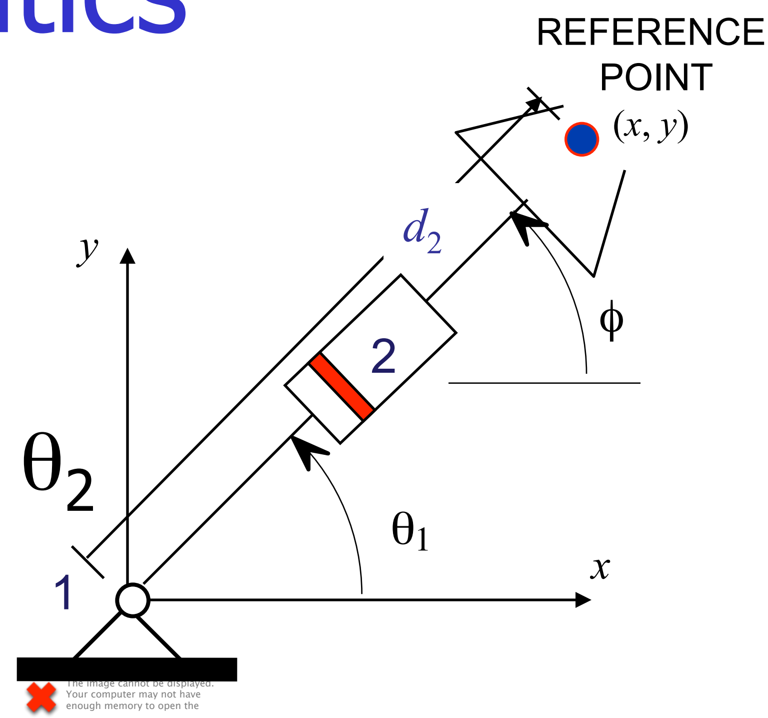
$$\phi = \theta_1$$

Given x, y, solve for θ_1, d_2

Inverse kinematics

$$x = d_2 \cos\theta_1$$
$$y = d_2 \sin\theta_1$$

- Given *x*, *y*, solve for θ_1, θ_2



Solution

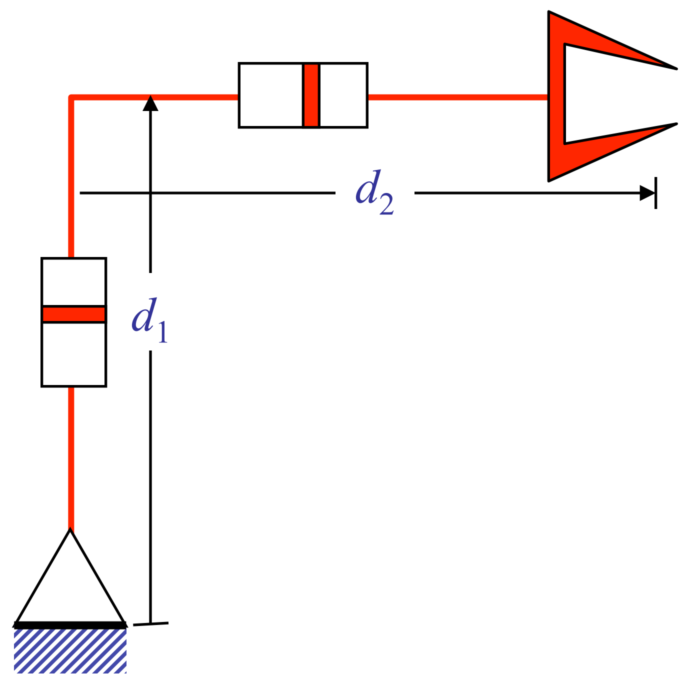
$$d_2 = +\sqrt{x^2 + y^2}$$
$$\theta_1 = \tan^{-1}\left(\frac{y}{x}\right)$$

Inverse kinematics

$$x = d_2$$

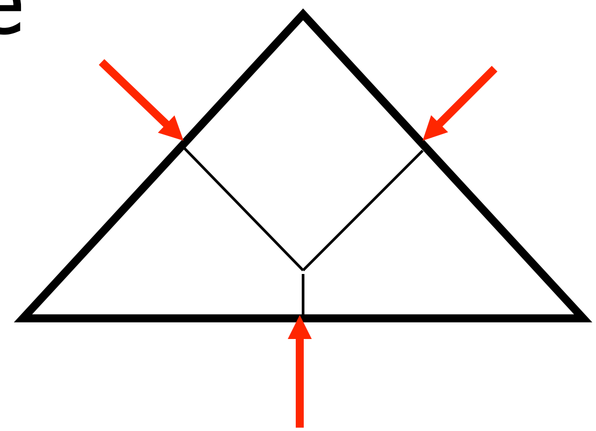
$$y = d_1$$

- Given x, y, solve for d_1, d_2
  - Direct and inverse kinematics are trivial
  - Only one solution
    - Equations are linear
    - No trigonometric functions
  - Popular geometry
    - CNC machines
    - Gantry robots
    - Plotters, special-purpose transfer devices



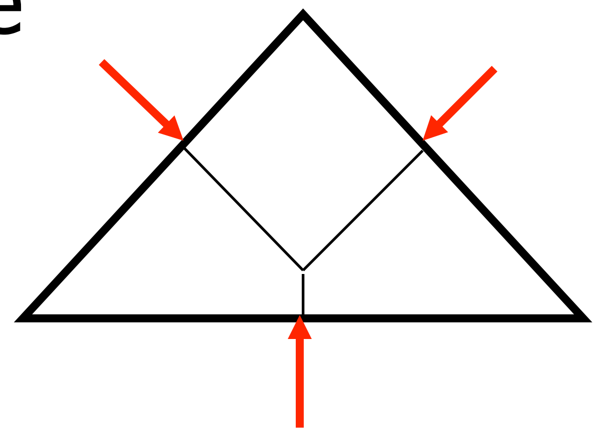
Grasp Analysis (no friction)

- Force-direction closure

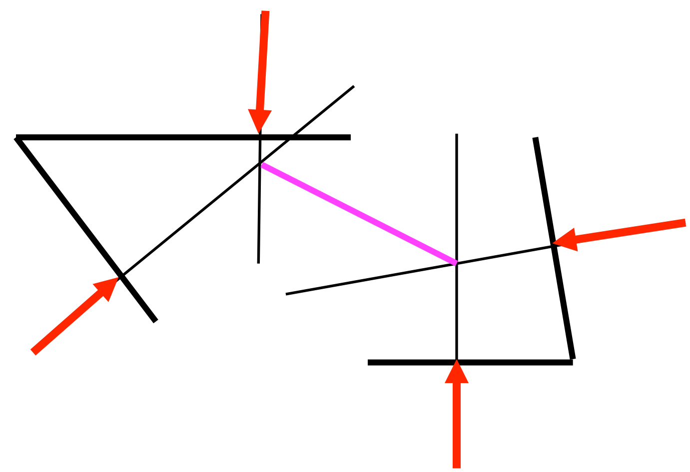


Grasp Analysis (no friction)

- Force-direction closure



- Torque closure

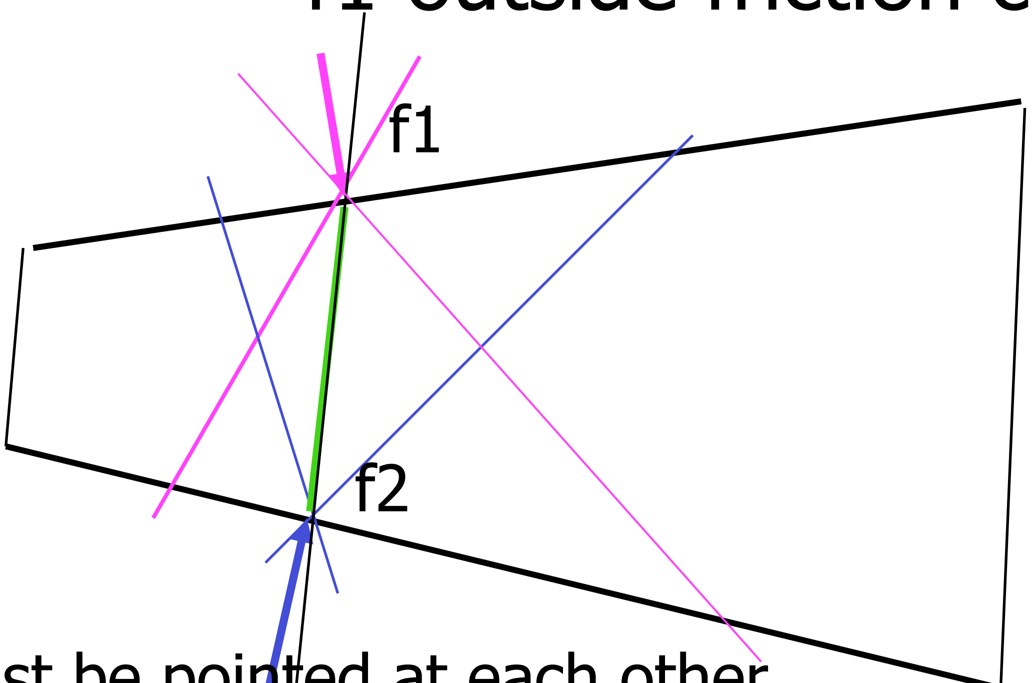


How do we turn this into an algorithm for grasping?

- Locus of A1
- Locus of A2
- Legal directions between A1 and A2
- Then
- Pick a line
- Convert to A1, A2,
- Project to get grasping points

Grasp Analysis (friction)

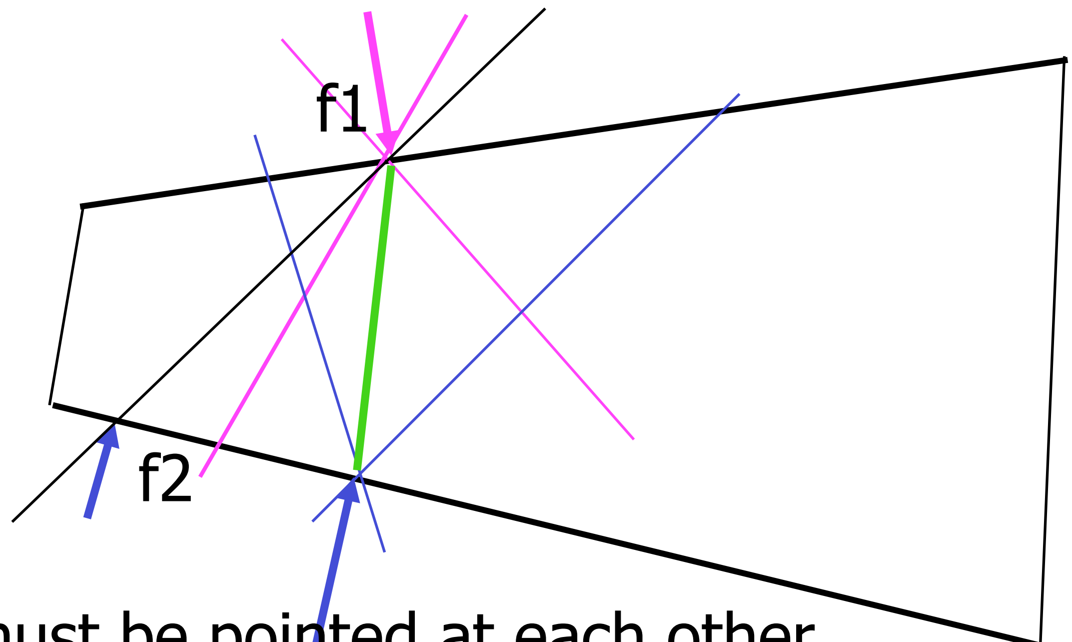
- With friction: f1 within friction cone--stick
  & f1 outside friction cone--slide



Forces must be pointed at each other
If blue force is anywhere within pink cone pink force
can be pointed at it; can the blue force be pointed at pink force?

Grasp Analysis (friction)

- With friction (stick vs slide)



Forces must be pointed at each other
If blue force is outside pink cone pink force can not
 be pointed at it because it will start slipping