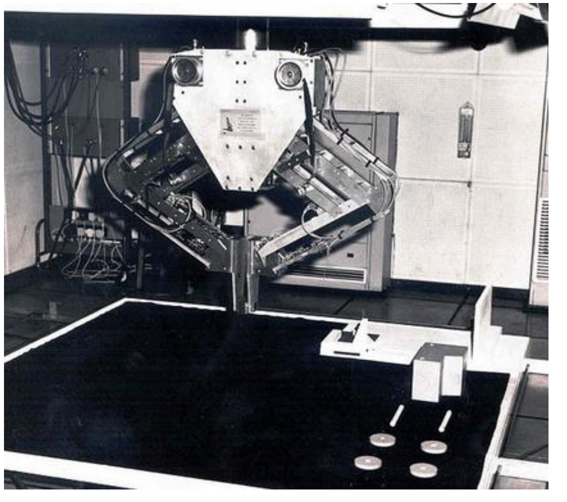
Lecture **11**: (23/02/15)

# Reaching and Grasping

- Reference Frames
- Configuration space
- Reaching
- Grasping



Michael Herrmann

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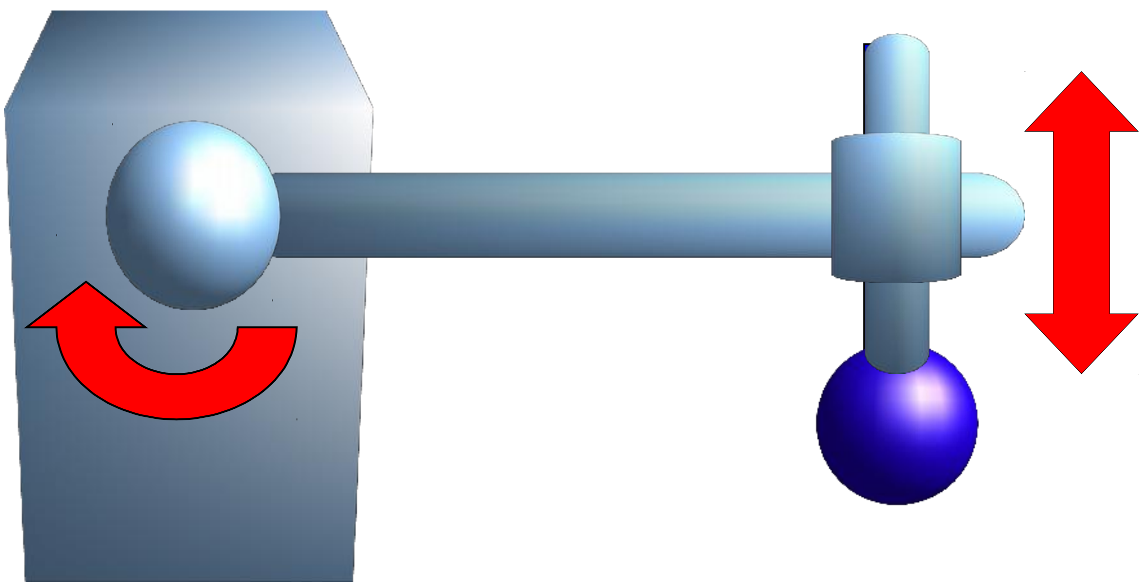
# Robot arms

- Typically constructed with rigid *links* between movable one d.o.f. *joints*
- Joints typically
  - *rotary* (revolute) or *prismatic* (linear)



# Kinematic pairs

Lower pairs

- Rotary (hinge, 1 axis)
- Prismatic (linear)
- Cylindrical (rotary + linear)
- Spherical (3 rotary)
- Planar (2 linear + rotary)

Higher pairs (different curvature): rolling bearing, cam joint, …

Wrapping pair: belt, chain, …

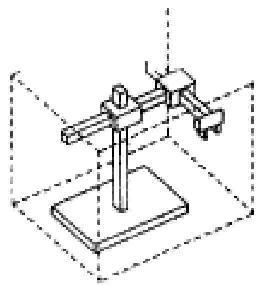
⇨ Linkages: Crankshaft-piston, …

⇨ Kinematic chains

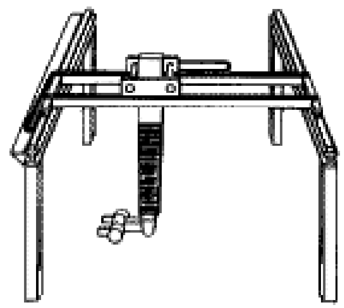
# Robot arms
## (manipulators)

Classification by geometry

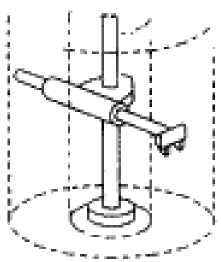
Variants



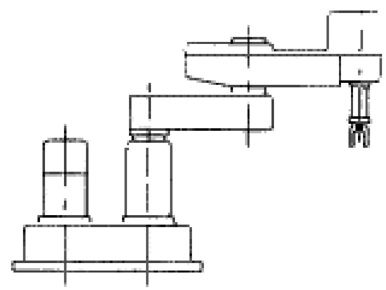
Rectangular Coordinate Robot



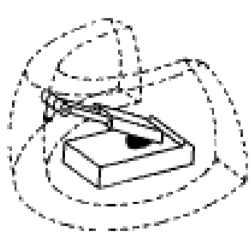
Gantry Robot



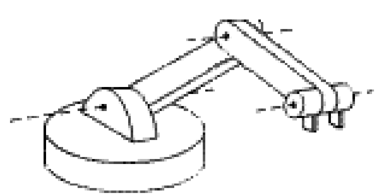
Cylindrical Coordinate Robot



SCARA Robot



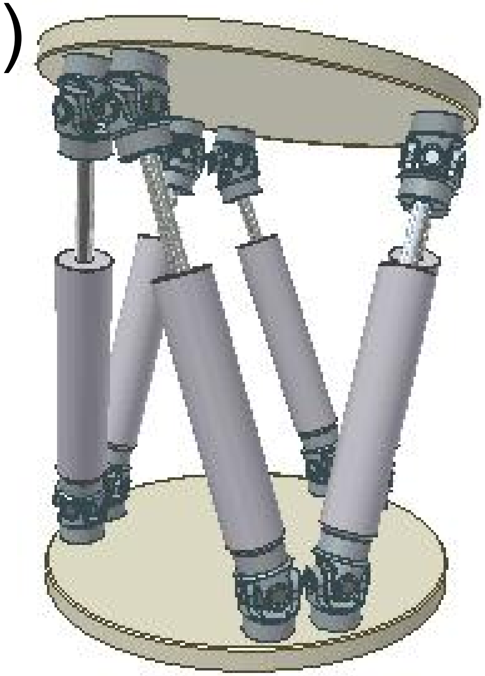
Sperical Coordinate Robot



Articulated Arm Robot

Classification by topology (kinematic chain):

- (left) Serial chain
- Parallel manipulator (below)

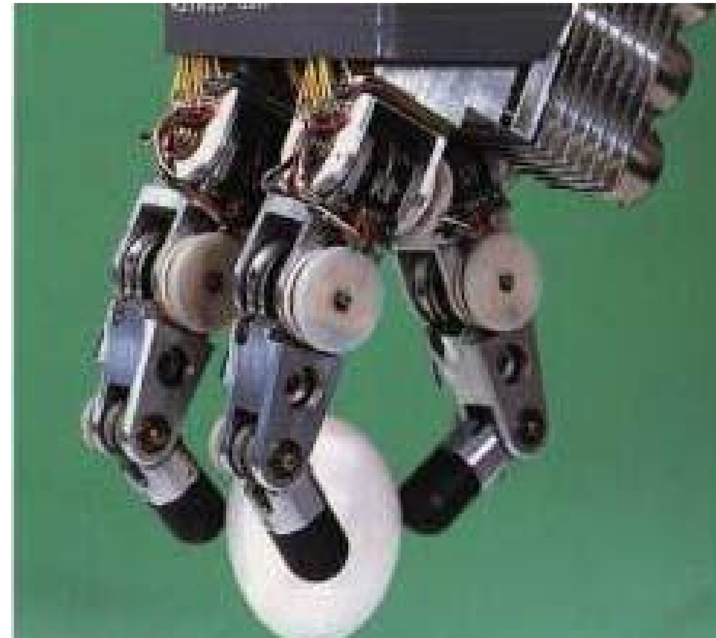


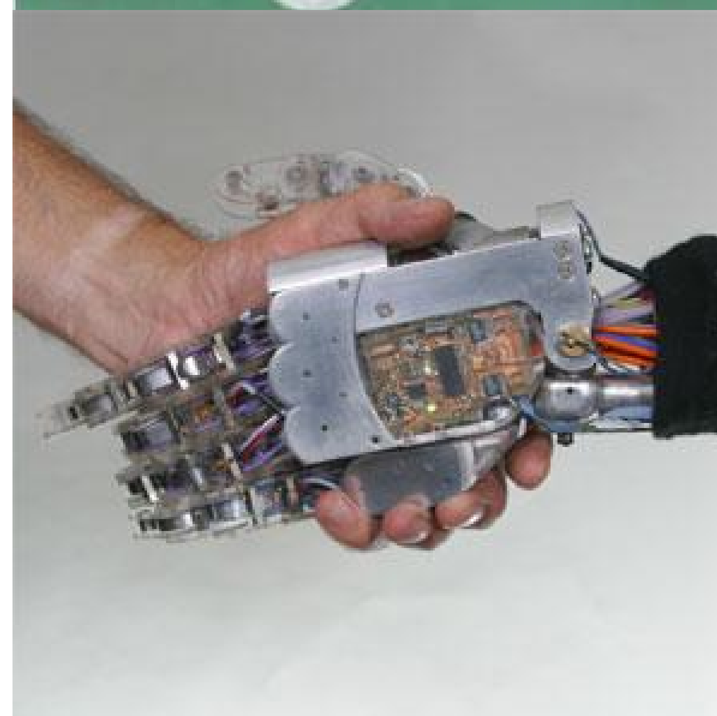
adapted from http://www.osha.gov/dts/osta/otm/otm_iv/otm_iv_4.html

fr.wikipedia.org

# Robot arm: End effectors (at Tool Center Point at top of kinematic chain)

- Simple push or sweep
- Gripper – different shape, size or strength
- Hook, pins, needles (e.g. for handling textiles)
- Vacuum cup, magnetic
- Adhesion by contact (e.g. glue)
- Tools for specific purposes (drills, welding torch, spray head, scalpel, scoop,…)
- Hand for variety of purposes





# Issues in choosing actuators

- Load (e.g. torque to overcome inertia of arm)
- Speed (fast enough but not too fast)
- Accuracy (will it move to where you want?)
- Resolution (can you specify exactly where?)
- Repeatability (will it do this every time?)
- Reliability (mean time between failures)
- Compliance (how does stiffness change?)
- Power consumption (how to feed it)
- Energy supply & its weight
- Geometry (linear vs. rotary) and other trade-offs between physical design and ability to *control*

# Prehension

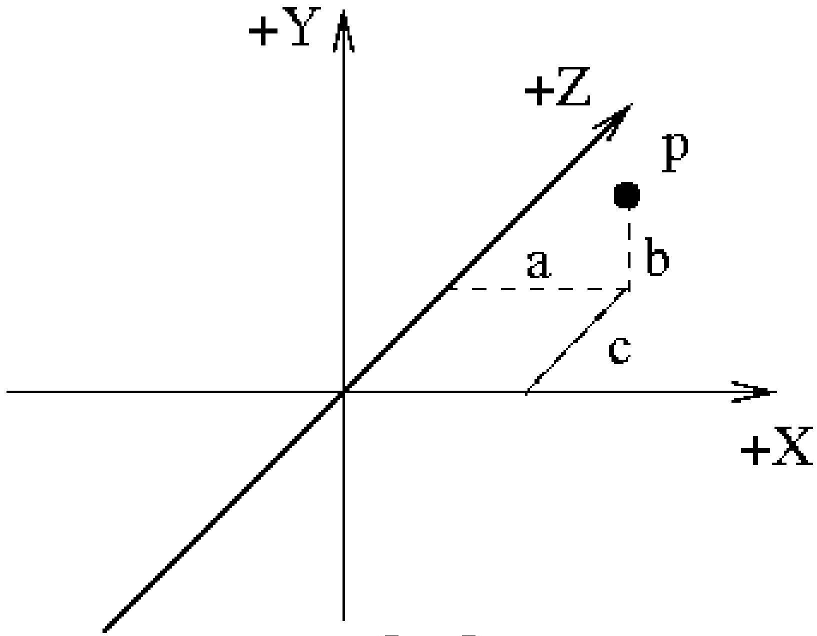
Goal: Understand ideal robot mechanisms for reaching, grasping and manipulation

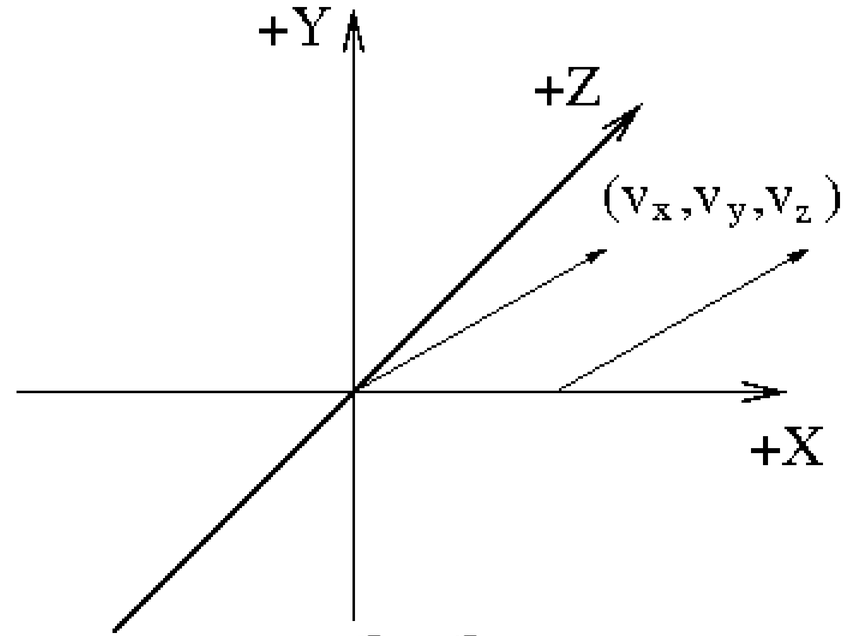
Robot positions and configurations as a function of control parameters – **kinematics**

*Need to know:*

- Representing mechanism geometry
- Standard configurations
- Degrees of freedom
- Grippers and graspability conditions

# Vectors & Points in 3D



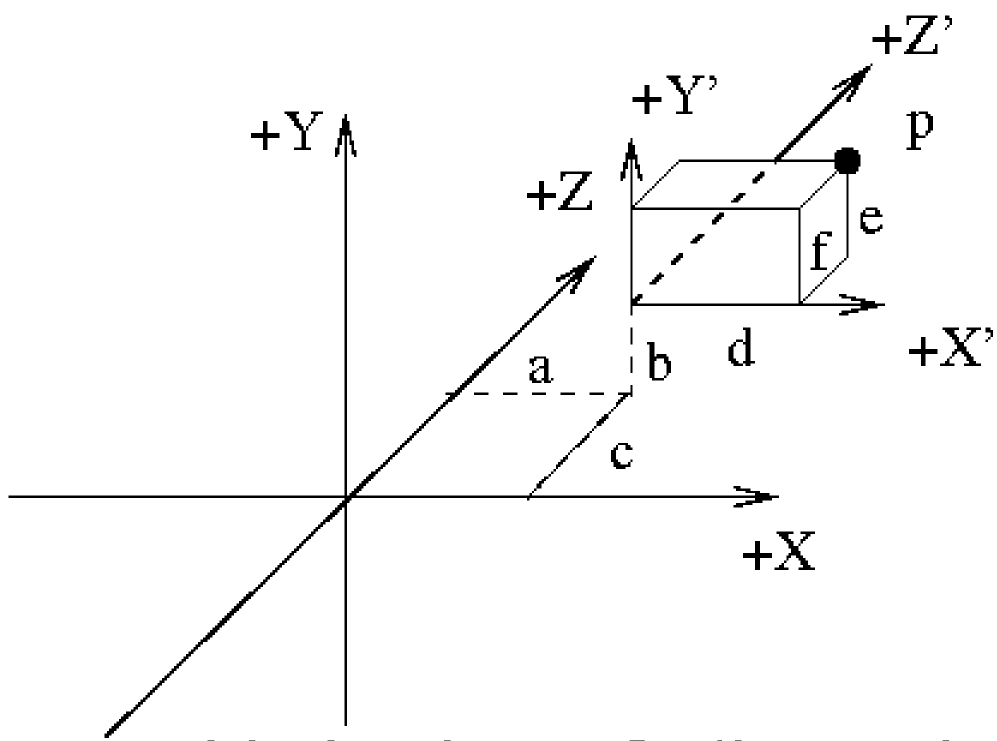

Point $\vec{p}=\begin{bmatrix} a \\ b \\ c \end{bmatrix}=\left(a, b, c\right)^T$ Vector $\vec{v}=\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}=\left(v_x, v_y, v_z\right)^T$

3D Coordinate Systems usually defined as left handed (right handed reverses the +*Z* direction)

# Local Reference Frames

$\vec{p}$ can be expressed by

- Local (translated) coordinates $\left(d, e, f\right)$
- Global (untranslated) coordinates $\left(a+d, b+e, c+f\right)$

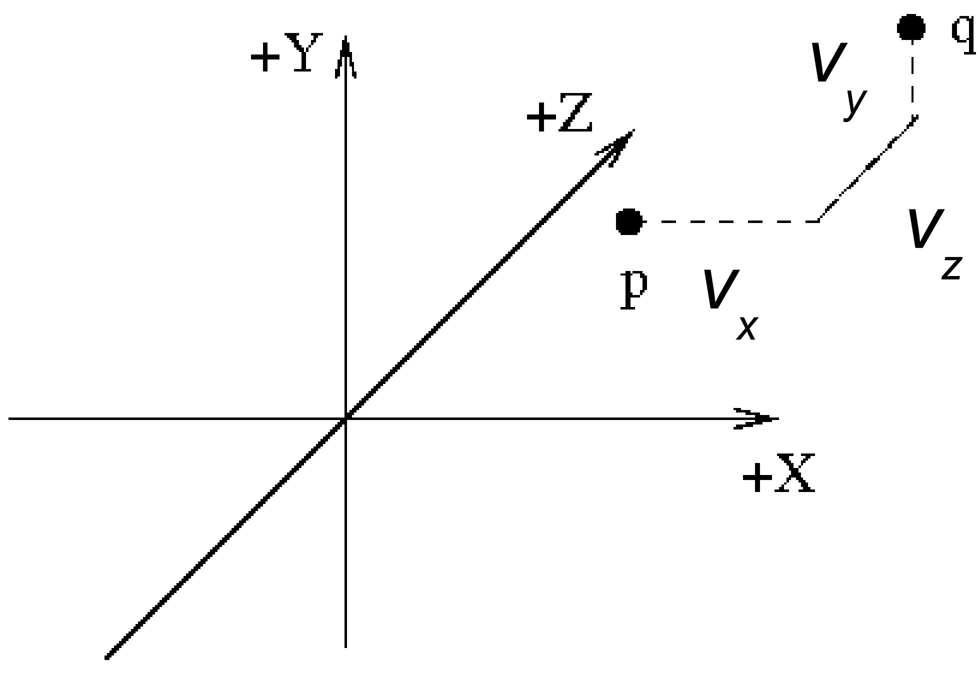



Local frame could also have further sub-local frames

# Translations

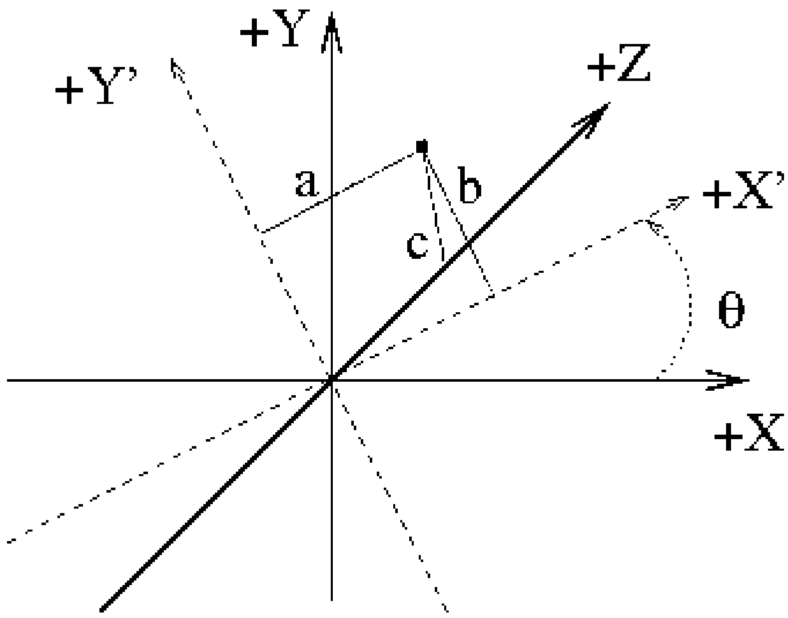
Move $\vec{p}$ to $\vec{q}$ :

$$\vec{q} = \vec{p} + \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}$$



# Rotations

Rotate about *Z* axis




A lot of conventions

Here: θ positive is anti-clockwise when looking along +*Z*

- $\vec{p}$ in local (rotated) coordinates is $(a,b,c)^{T'}$
- $\vec{p}$ in global (unrotated) coordinates is
  $(a\cos(\theta)-b\sin(\theta),\ a\sin(\theta)+b\cos(\theta),c)^{T}$

# Rotation Matrix Representation I

$$\vec{p} = (a, b, c)^{\mathsf{T}} \longrightarrow (a \times \cos(\theta) - b \times \sin(\theta), a \times \sin(\theta) + b \times \cos(\theta), c)^{\mathsf{T}}$$

$$R_z(\theta_z)\vec{p} = \begin{bmatrix} \cos(\theta_z) & -\sin(\theta_z) & 0 \\ \sin(\theta_z) & \cos(\theta_z) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

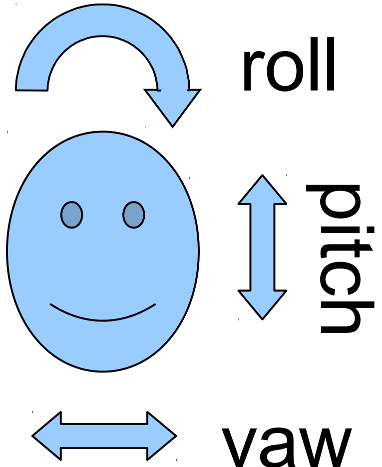
Much more compact and clearer!

# Rotation Matrix Representation II

$$R_x(\theta_x)=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos(\theta_x) & -\sin(\theta_x)\\ 0 & \sin(\theta_x) & \cos(\theta_x)\end{bmatrix}$$

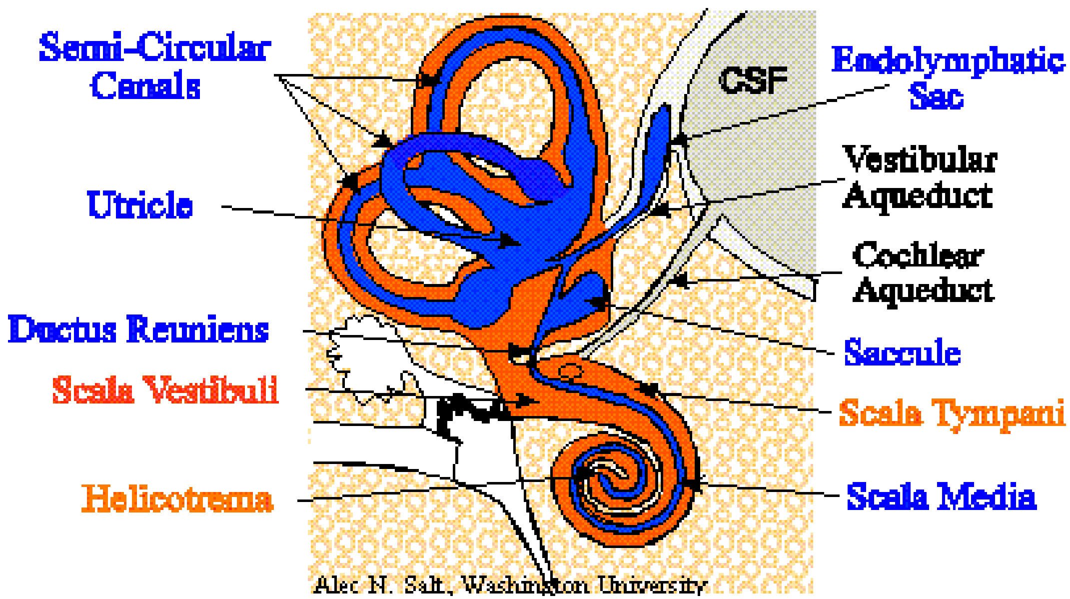
$$R_y(\theta_y)=\begin{bmatrix}\cos(\theta_y) & 0 & \sin(\theta_y)\\ 0 & 1 & 0\\ -\sin(\theta_y) & 0 & \cos(\theta_y)\end{bmatrix}$$

# Other Rotation Representations




All equivalent but different parameters:

- Yaw, pitch, roll
- Azimuth, elevation, twist
  (slant, tilt, twist)
- Axis + angle
  → Quaternions
- N.B.: in mammals:



# Full Rotation Specification

- Need 3 angles for arbitrary 3D rotation
- Lock & key example (axis and direction of key bit)
- Rotation angles $(\alpha, \beta, \gamma)$:

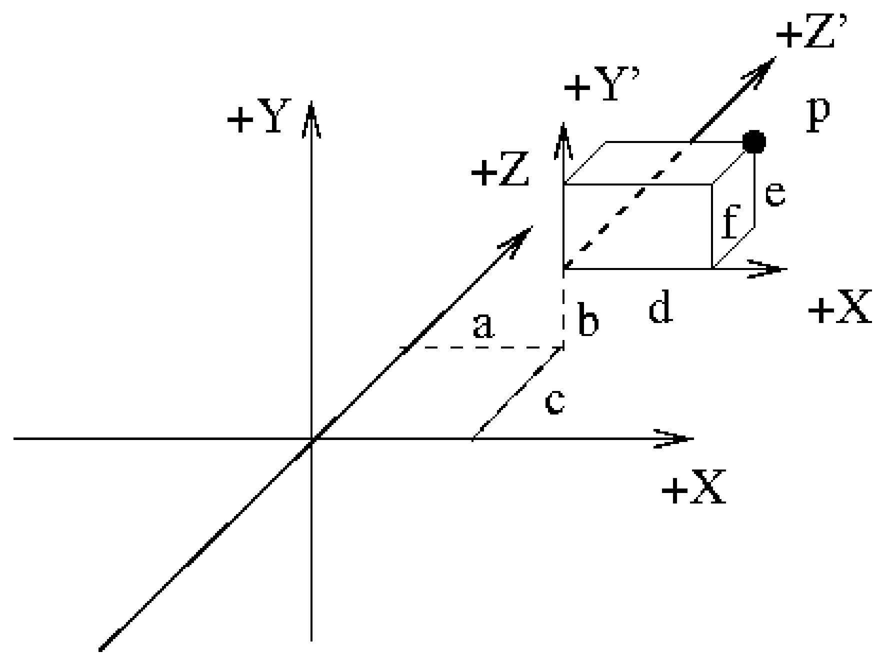
$$R(\alpha, \beta, \gamma)p = R_z(\gamma)R_y(\beta)R_x(\alpha)p$$

- Warning: rotation order by convention but must be used consistently:

$$R_z(\gamma)R_y(\beta)R_x(\alpha) \neq R_x(\alpha)R_y(\beta)R_z(\gamma)$$

# Full Transformation Specification

Each connection has a new local coordinate system

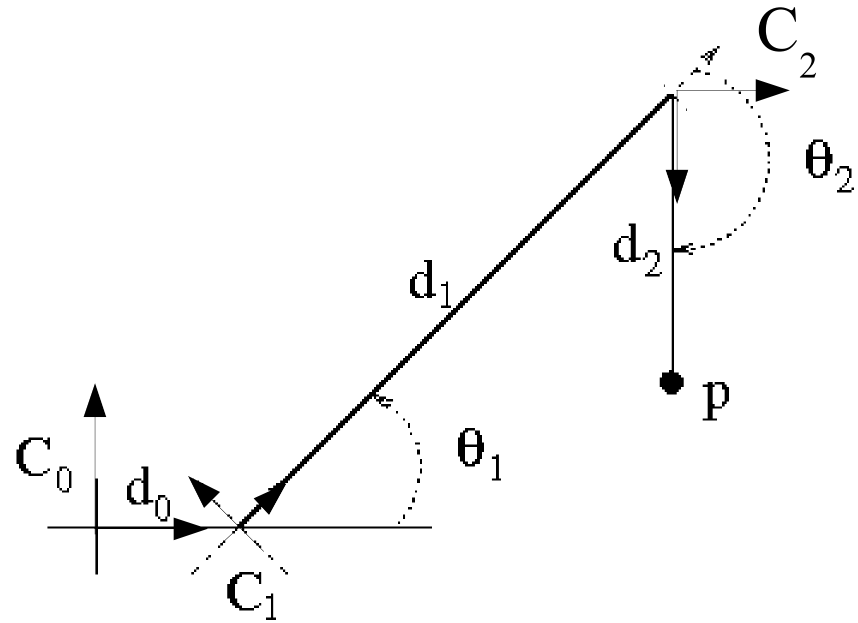



Need to specify
6 degrees
of freedom =
3 rotation + 3 translation

$$\text{transform}(\theta_x, \theta_y, \theta_z, t_x, t_y, t_z) = \text{trf}(\theta, t)$$

# Kinematic Chains in 2D

$p$ is:




in $C_2$: $\begin{pmatrix} d_2 \\ 0 \end{pmatrix}$

in $C_1$: $R(\theta_2)\begin{pmatrix} d_2 \\ 0 \end{pmatrix} + \begin{pmatrix} d_1 \\ 0 \end{pmatrix}$

in $C_0$: $R(\theta_1)[\,R(\theta_2)\begin{pmatrix} d_2 \\ 0 \end{pmatrix} + \begin{pmatrix} d_1 \\ 0 \end{pmatrix}] + \begin{pmatrix} d_0 \\ 0 \end{pmatrix}$

# Homogeneous Coordinates I

Messy when more than 2 links, as in robot
So: pack rotation and translation into

**Homogeneous coordinate matrix**

Extend points with a 1 from 3-vector to 4-vector
Extend vectors with a 0 from 3-vector to 4-vector
Pack rotation and translation into 4x4 matrix:

$$H_1 = \begin{bmatrix} R(\vec{\theta}_1) & \vec{t}_1 \\ \vec{0} & 1 \end{bmatrix}$$

3 rotation parameters: $\vec{\theta}_1$
3 translation parameters: $\vec{t}_1$

# Homogeneous matrices

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

rotations

$$\begin{pmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

translation

scaling

$$\begin{pmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

projection

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

perspective

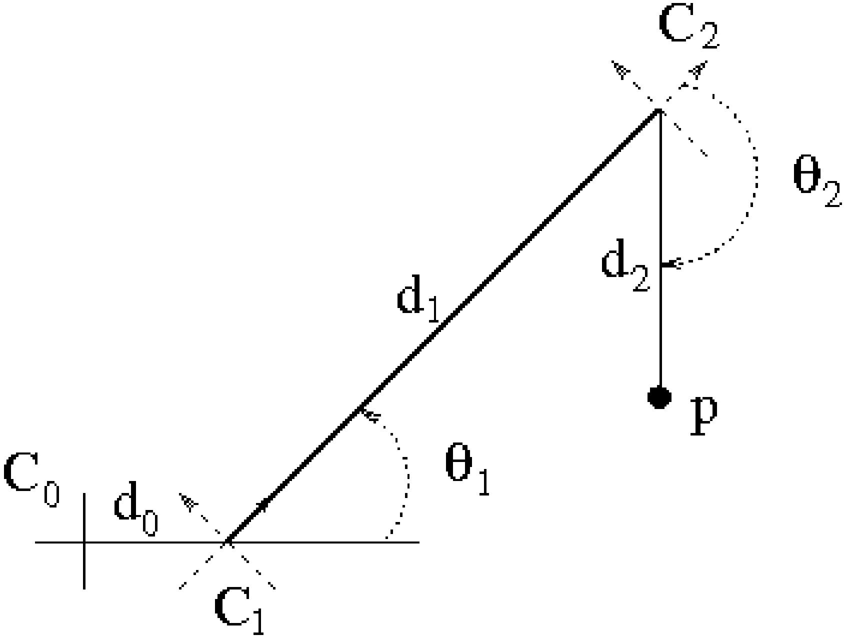
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{d} & 0 \end{pmatrix}$$

view plane z=0, center of projection at (0,0,-d)

Isometries also represented as 6D vector: trf($\alpha,\beta,\gamma,l_x,l_y,l_z$)

# Homogeneous coordinates II

$$\vec{p}^{\,*} = \begin{pmatrix} \vec{p} \\ 1 \end{pmatrix}$$




In $C_2$: $p^*$

In $C_1$: $H_2 p^*$

In $C_0$: $H_1 H_2 p^*$

Longer chains for robot arms (e.g. 6 links):

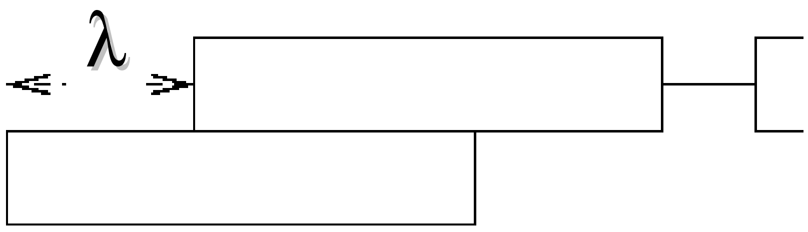
$$H_1 H_2 H_3 H_4 H_5 H_6 p^*$$

# Joint geometry

Linear (prismatic) joint:
- slides
- parametrize one translation direction per joint

e.g. Sliding in the *x* direction

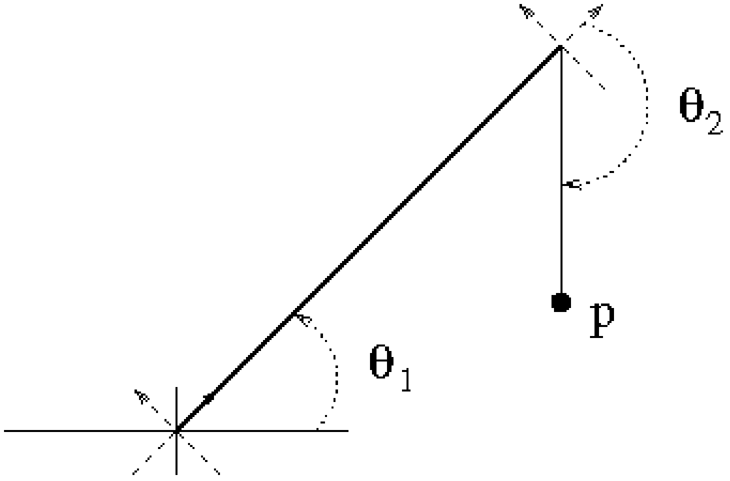
trf(0,0,0,$\lambda$,0,0)




Hinge (revolute) joint:
- rotates
- parametrize one rotation angle per joint

e.g. Rotation about *x*-axis

trf($\theta$,0,0,0,0,0)



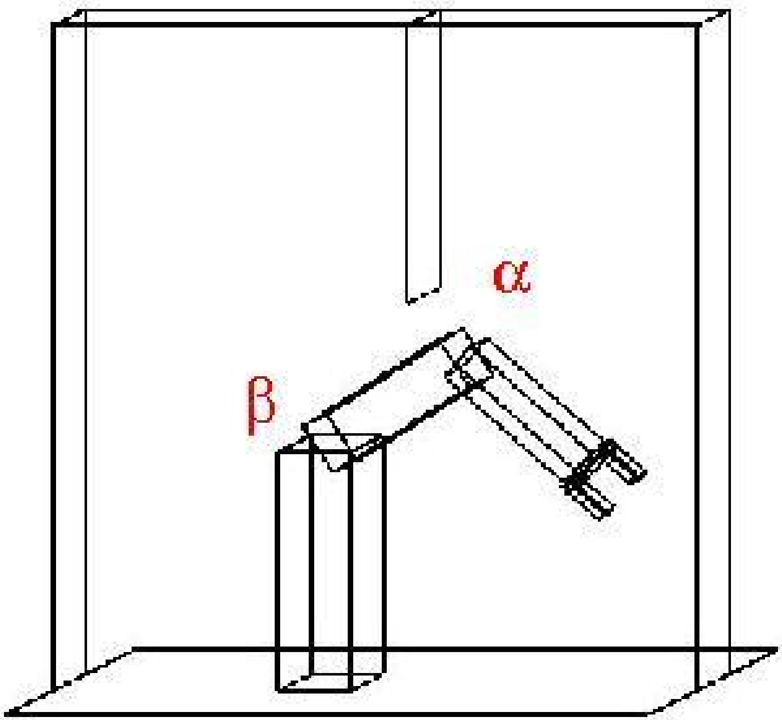
# Configuration Space I

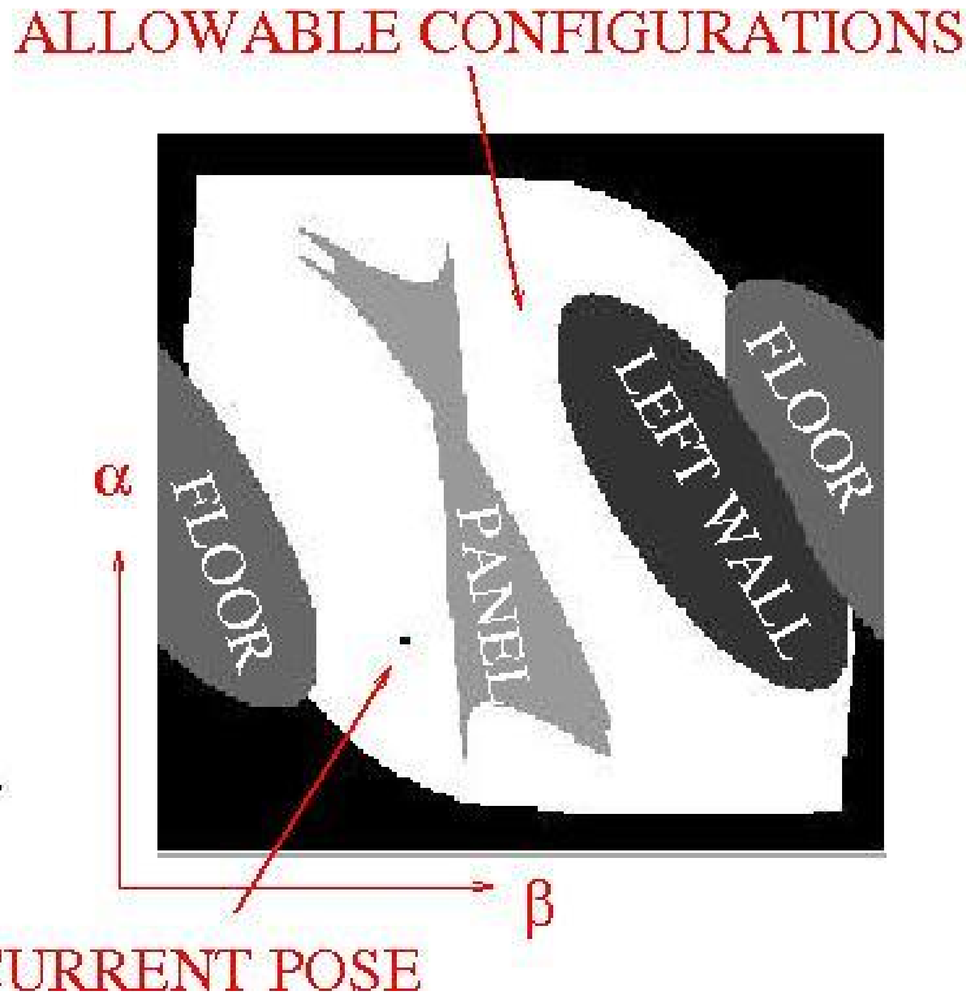
Alternative representation to scene coordinates

Number of joints = *J*
*J*-dimensional space
- Binary encoding: *0* for invalid pose, *1* for free space
- Real-valued encoding:
  "distance" from goal configuration

Point in C.S. = configuration in real space
Curve in C.S. = motion path in real space

# Configuration Space II

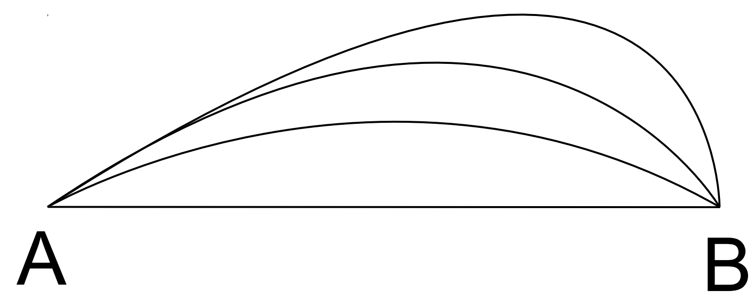


# Dynamics: Trajectory Planning

What is the shortest path in configuration space?
At what speed the path is traversed?

- Cost to go (energy or wear)
- Time to goal
- Least perturbations (predictability)
- Maximal smoothness
- Minimal intervention



# Forward and Inverse Kinematics

Forward:

Given joint angles, find gripper position
Easy for sequential joints in robot arm:
just multiply matrices

Inverse:

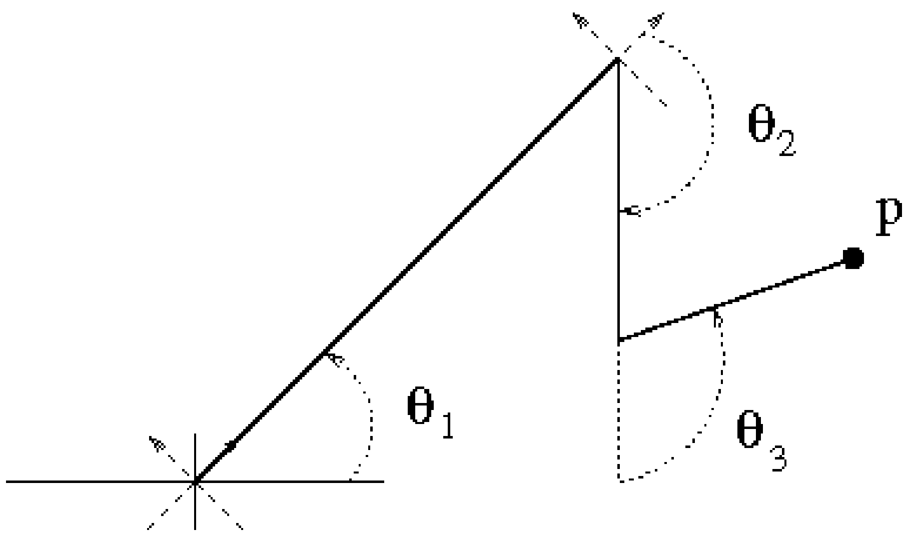
Given desired gripper position, find joint angles
Hard for sequential joints – geometric reasoning

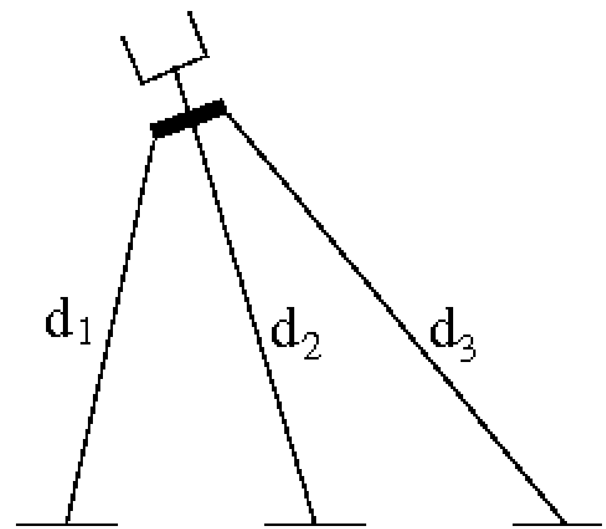
# Sequential & Parallel Mechanisms

Simplified into 2D

Serial manipulator
vary: $\theta_1, \theta_2, \theta_3$

Parallel manipulator
vary: $d_1, d_2, d_3$



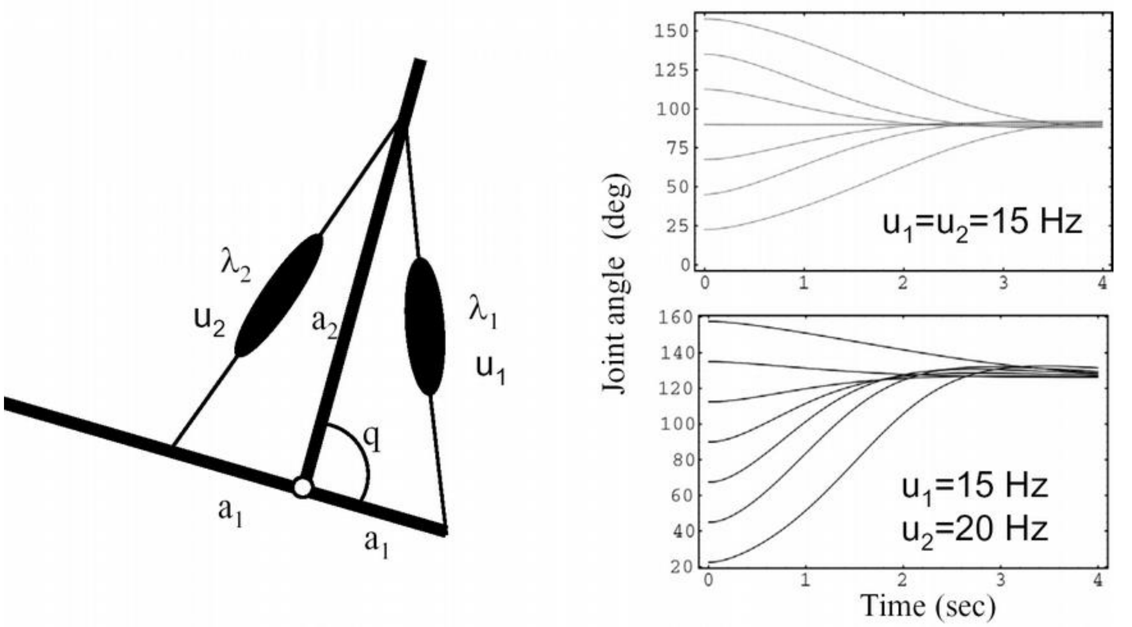



# Computing Positions & Parameters

| | Serial | Parallel |
|---|---|---|
| Forward (param->position) | Easy (just multiply matrices) | Hard (messy robot specific geometry) |
| Inverse (position->param) | Hard (messy robot specific geometry) | Easy (just read off lengths from gripper position) |

N.B.: Biological motor control

# Equilibrium point hypothesis




A. G. Feldman 66
Bizzi et al. 78
Gribble et al. 98

- Extensors and flexors controlled by different pathways:
- Force-field experiments: violation of equifinality at variations of velocity-dependent load (Hinder & Milner 03)

⟶ Solution: Internal dynamics models (Shadmehr & Mussa-Ivaldi 94)

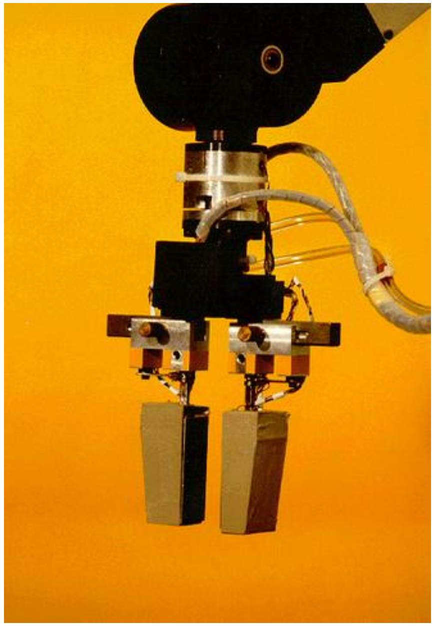
# Specifying Robot Positions

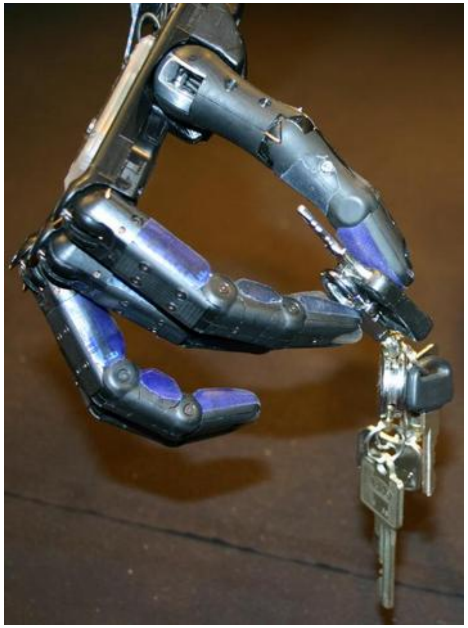
1. Actuator level: specify voltages that generate required joint angles.
2. Joint level: specify joint angles and let system calculate voltages.
3. Effector level: specify tool position and let system compute joint angles.
4. Task level: specify the required task and let the system compute the sequence of tool positions

Most robot programming is at levels 2 and 3.

# Grippers and Grasping

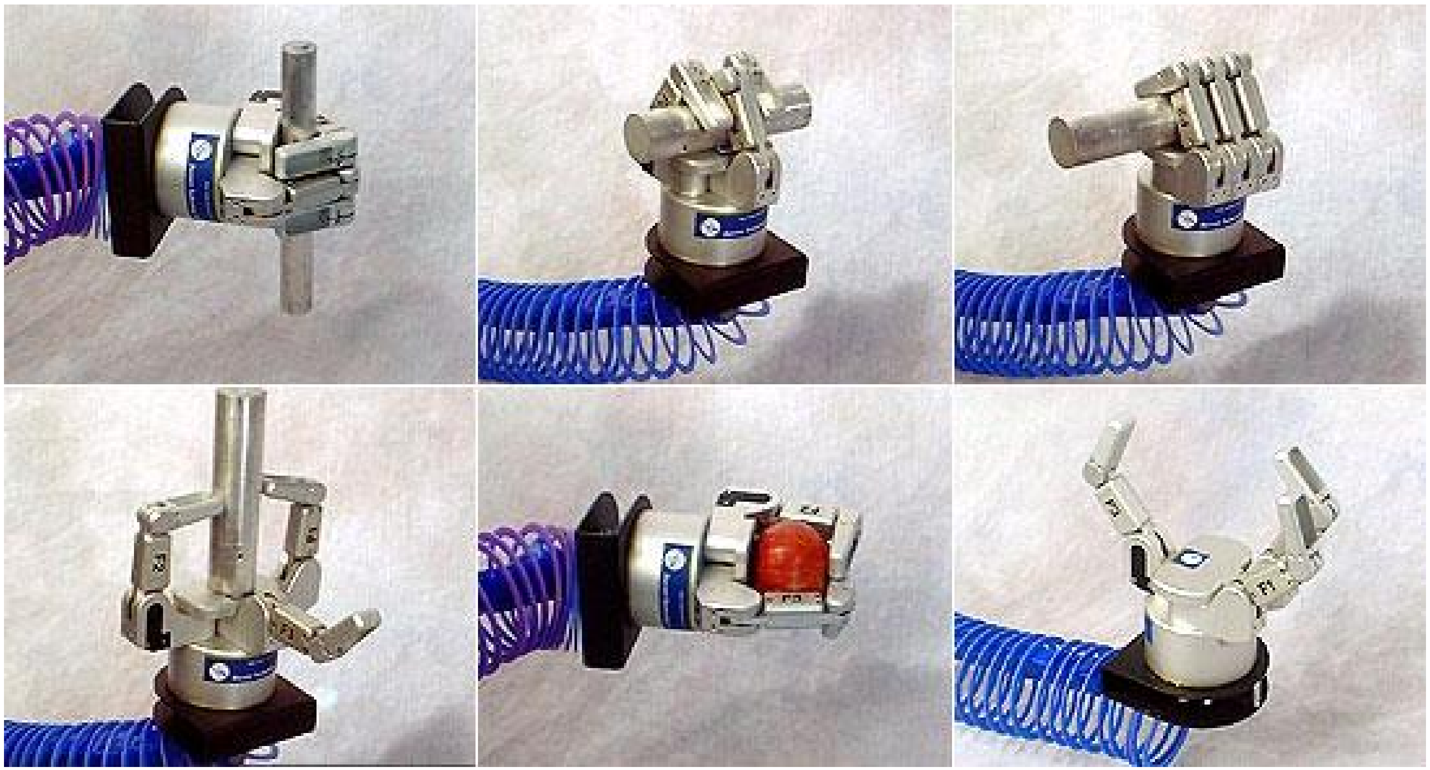
- Gripper: special tool for general part manipulation
- Fingers/gripper: 2, 4, 5
- Joints/finger: 1, 2, 3





Your hand: 4 fingers * 4 DoF + thumb * 5 DoF+ wrist * 6 DoF  = 27 DoF (22 controllable DoF).

# Barrett Technology Hand

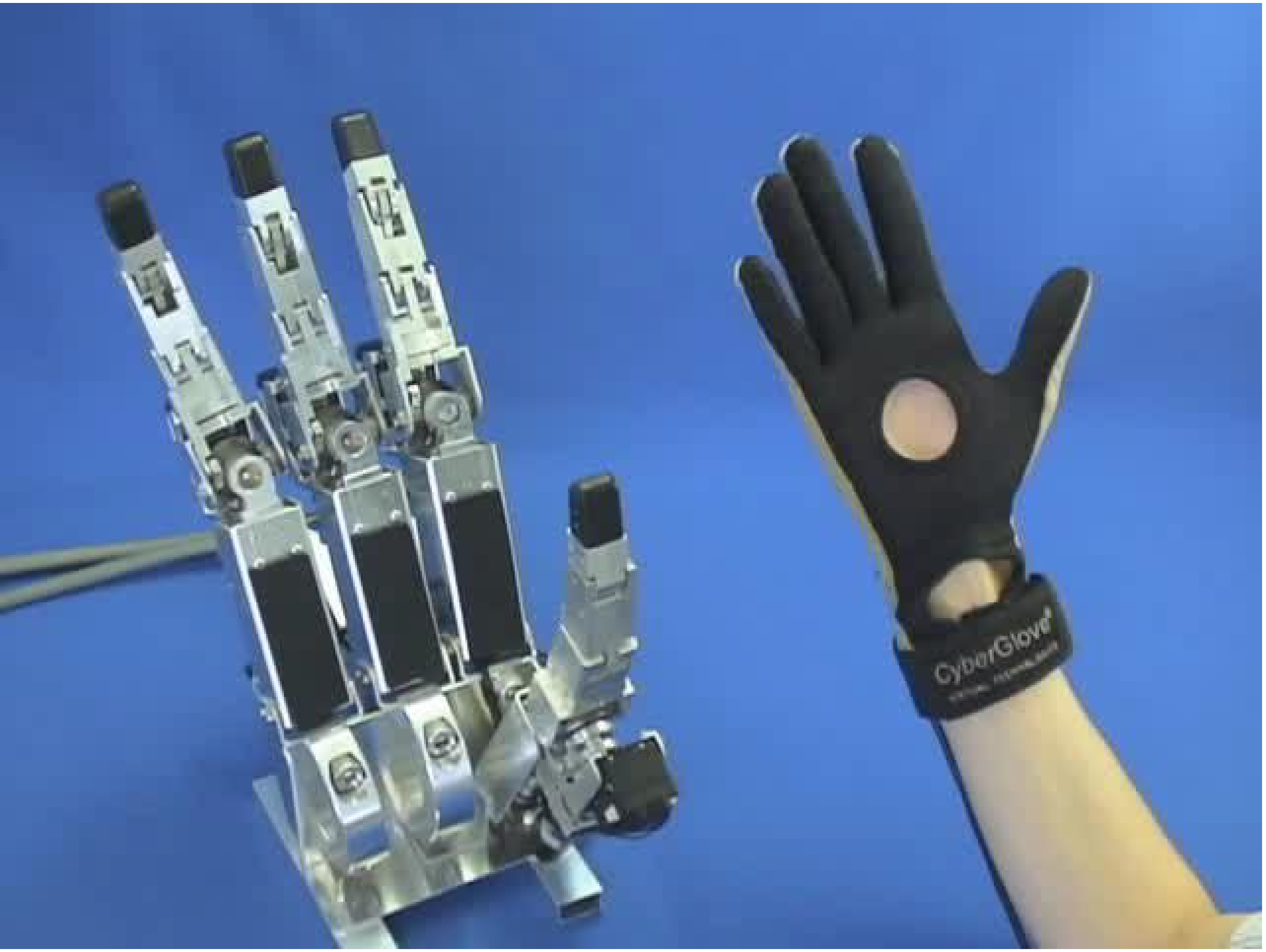


2 parallel fingers (spread uniformly)

1 opposable finger

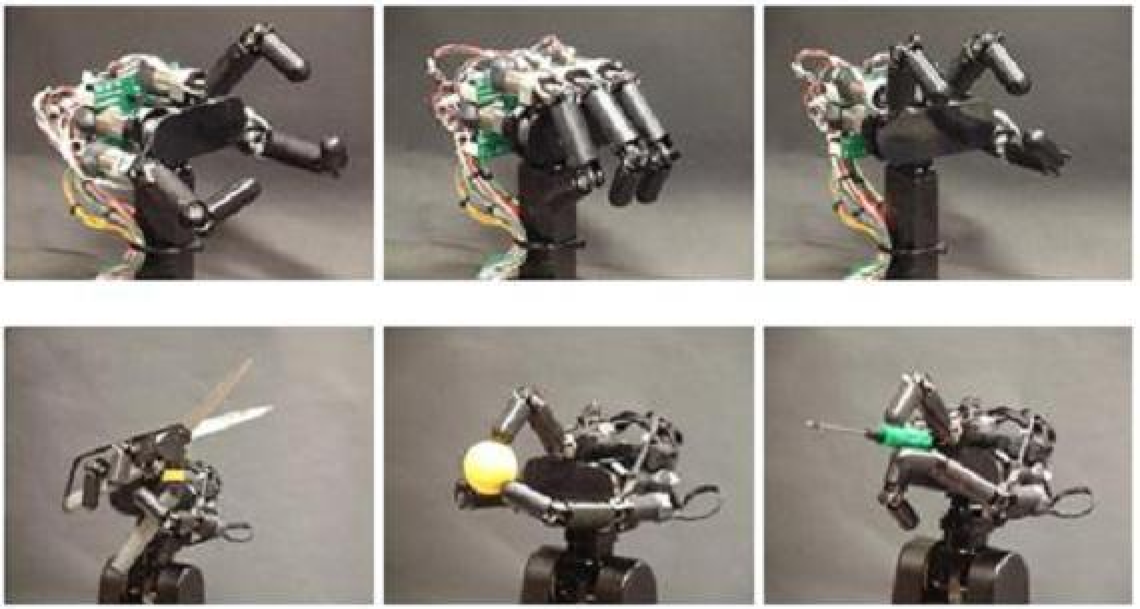
DoF: 4 fingers (2 finger joints bend uniformly)

# Shadow Dextrous Robot Hand




http://www.shadowrobot.com/hand/

# High-Speed Robotic Hand

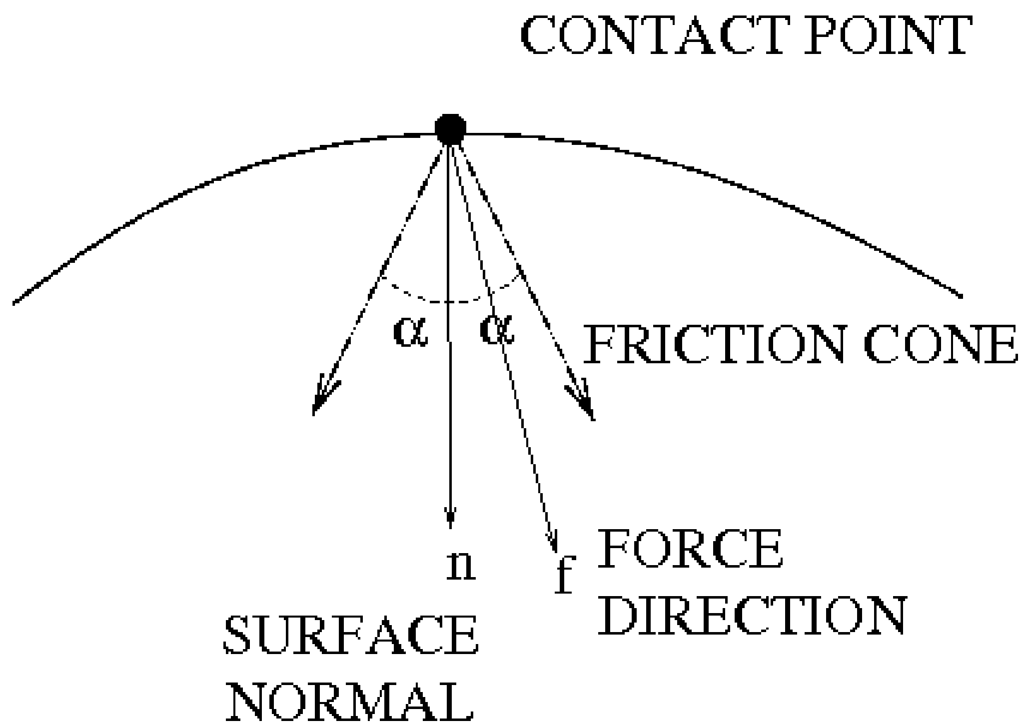


Ishikawa Komuro


# Finger Contact Geometry

- Coefficient of friction at fingertip: $\mu \in [0,1]$
- Surface normal: Direction perpendicular to surface: $\vec{n}$
- Friction cone: Angles within $\alpha = \cos^{-1}(\mu)$ about surface normal
- Force direction: $f$ direction in which finger pushed
- No-slip condition:

$$\vec{f} \cdot \vec{n} \geq \mu$$



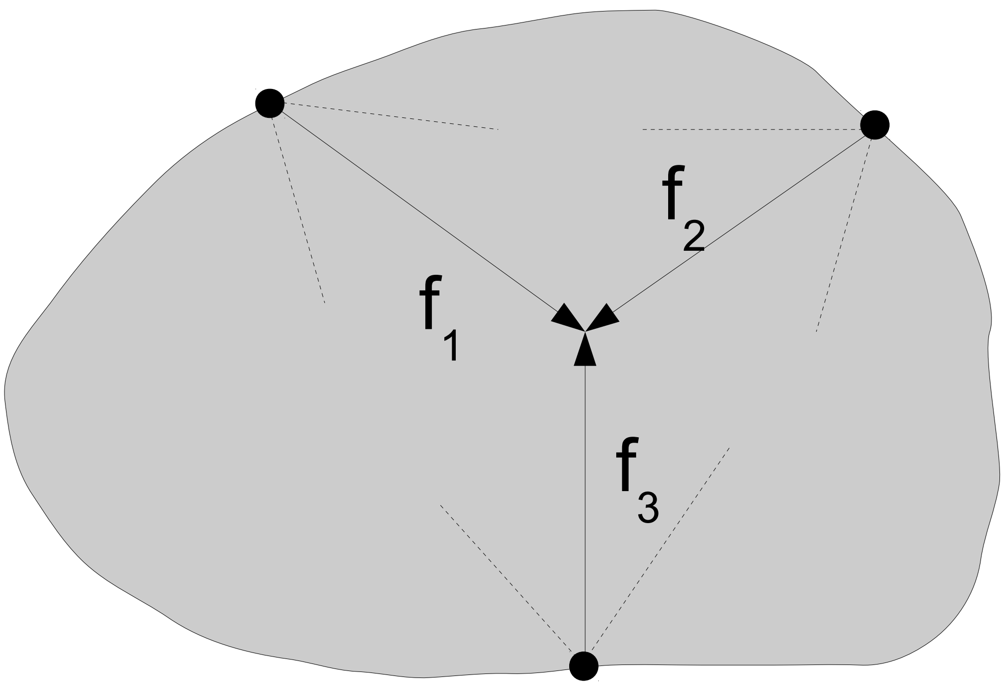
# Force Closure

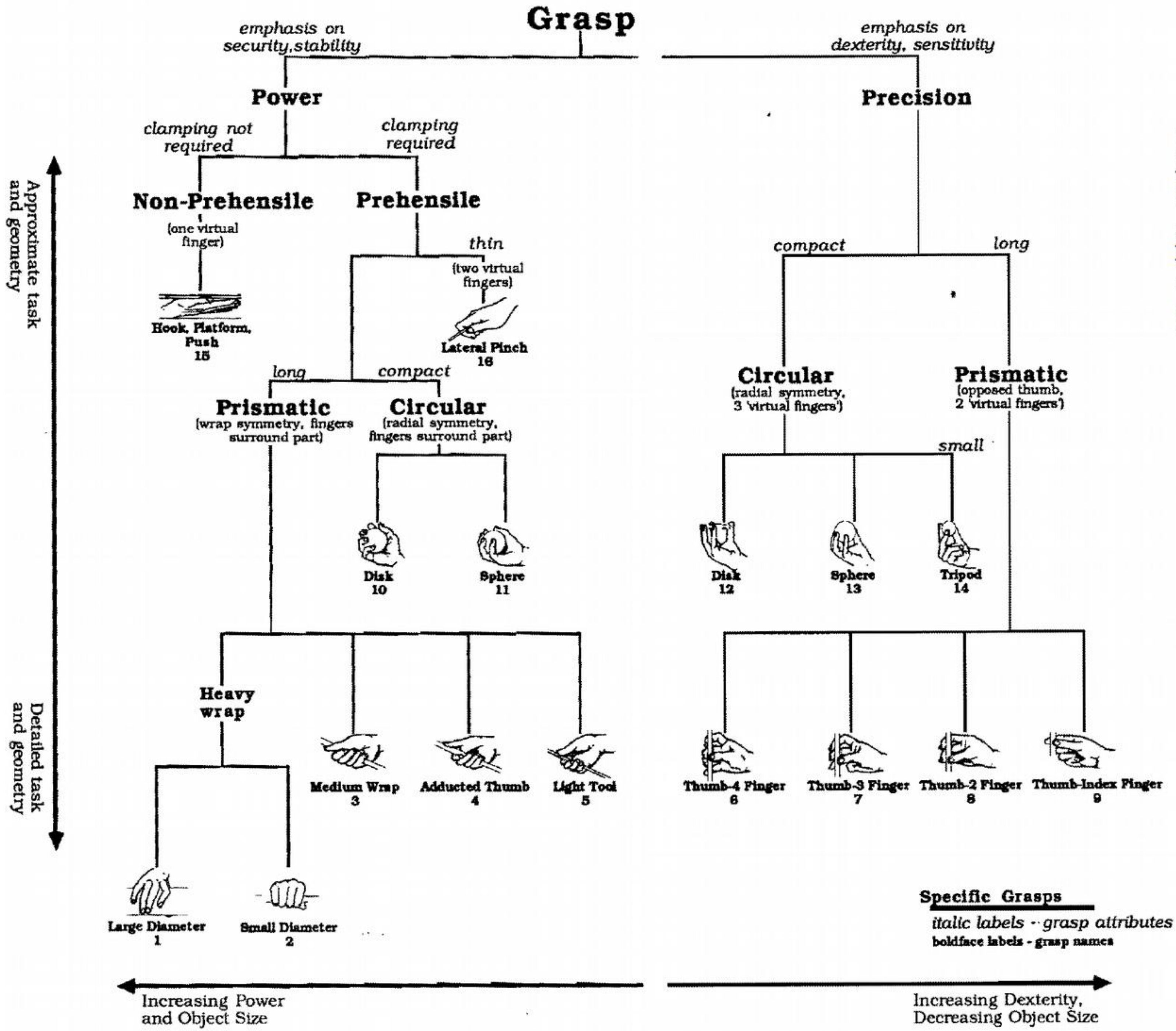
Need balanced forces or else object twists

- 2 fingers – forces oppose: $\vec{f}_1 + \vec{f}_2 = 0$
- 3 fingers – forces meet at point: $\vec{f}_1 + \vec{f}_2 + \vec{f}_3 = 0$

Force closure: point where forces meet lies within

- 3 friction cones otherwise object slips






MR Cutkosky and RD Howe, "Human Grasp Choice and Robotic Grasp Analysis," in ST Venkataraman, T Iberall, editors, *Dextrous Robot Hands*, Springer-Verlag, 1990, Chapter 1, pp 5-31.

# Other Grasping Criteria

Some heuristics for a good grasp:

- Contact points form nearly equilateral triangle
- Contact points make a big triangle
- Force focus point near Center of Mass (CoM)

# Grasp Algorithm

1. Isolate boundary
2. Locate large enough smooth graspable sections
3. Compute surface normals
4. Pick triples of grasp points
5. Evaluate for closure & select by heuristics
6. Evaluate for reachability and collisions
7. Compute force directions and amount
8. Plan approach and finger closing strategy
9. Contact surface & apply grasping force
10. Lift (& hope)

# Kinematics Summary

1. Need vector & matrix form for robot geometry
2. Geometry of joints & joint parameters
3. Forward & inverse kinematics
4. Degrees of freedom
5. Grippers & grasping conditions