Final Exam Review

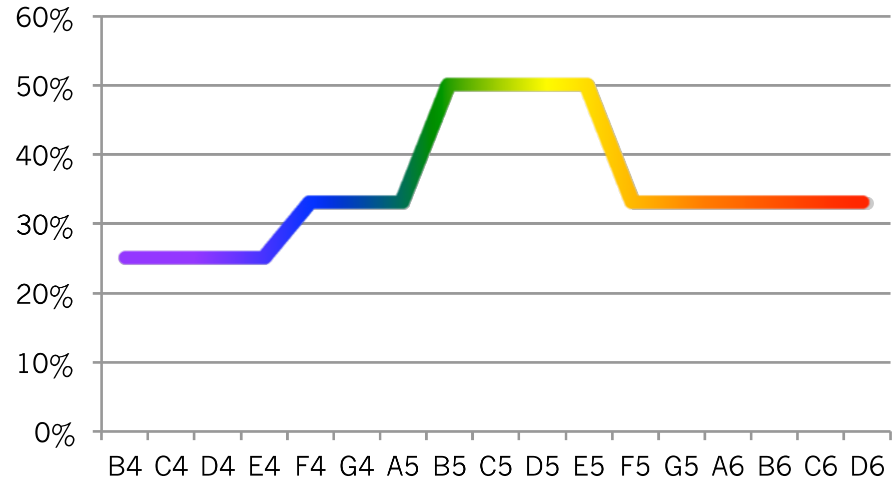
Dr. Matuszek

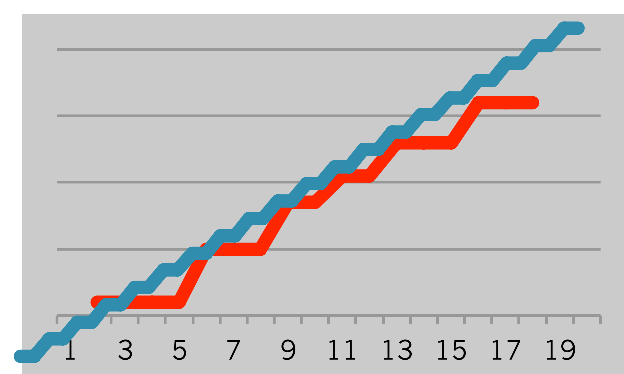
Main Concerns

- What kinds of questions will I ask?
  - Conceptually
  - Pragmatically
- What topics will be on the exam?

Types of Questions

- What Will I Ask?
- Multiple-choice, short answer, image-based
- Synthesis, e.g.:
  - What's the purpose of something?
  - How would you solve the following problem?
  - Examples:





See: <u>Q2 #1</u>, <u>Q3 #10, #14</u>, <u>Q4 #8, #17</u>

Topics

- What's a Robot?
- Sensing
- Uncertainty
- Actuators
- Control software
- Motors/motor control
- Locomotion
- Manipulation
- Kinematics
- Localization
- Motion planning
- Machine learning
- Cognition
- Human-robot interaction

What's a Robot?

- Overview and Concepts
  - What is a robot?

- Autonomous?
- Physical?
- Human-friendly?
- Humanoid?
- Sensory?
- Intelligent?
- Mobile?
- Manipulative?
- What else?

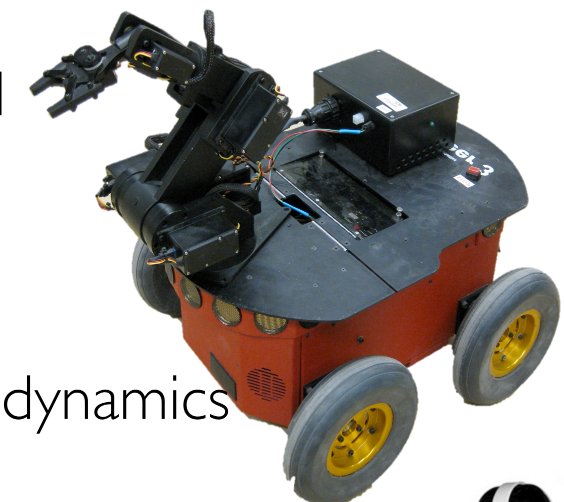
- Won't ask explicitly –be able to discuss intelligently

What Are They Good For?

- Now
  - Factories (how?)
  - Industrial automation (mining, harvesting, warehouses, …)
  - Surgery, vacuuming, surveillance, military, space
  - Homes: Toys, vacuuming, driving
- Future?
  - More of the above, plus:
  - Hazardous environments (space, underwater, battlefields, …)
  - Complex household tasks
  - Human-robot interaction

What Subsystems Are There?

- Sensing
  - Perceiving the world
- Actuation
  - Doing something in the (physical) world
  - Mobility, manipulation

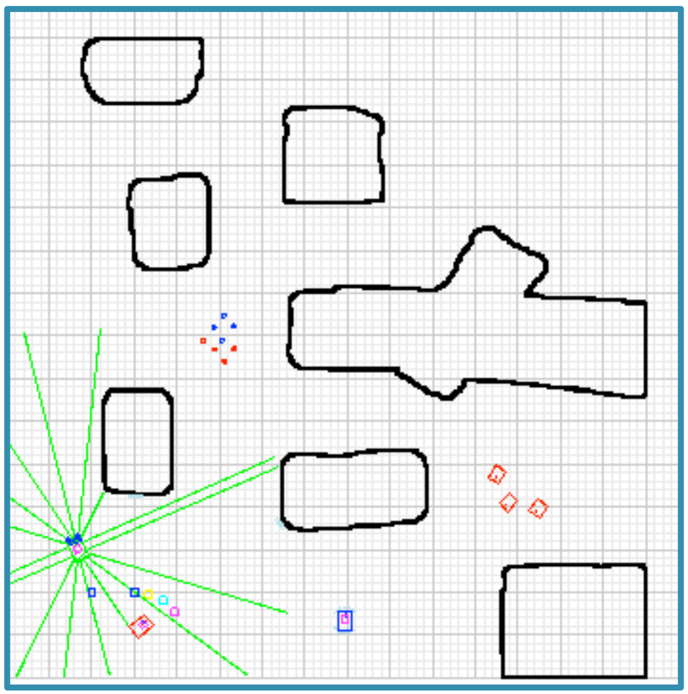


- Control
  - Navigation, motion planning, kinematics, dynamics
- Autonomy/Planning
- Interfaces (but we didn't really do this)

Very High Level View

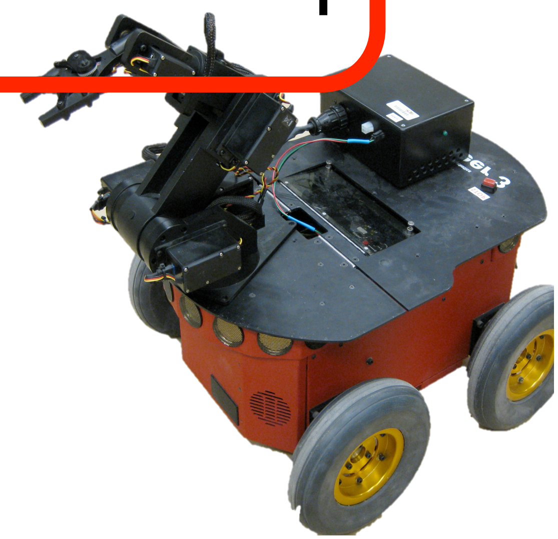
Without this: “open loop”

Sensor data



World Model

Control System



Actions

Mobility: Rolling

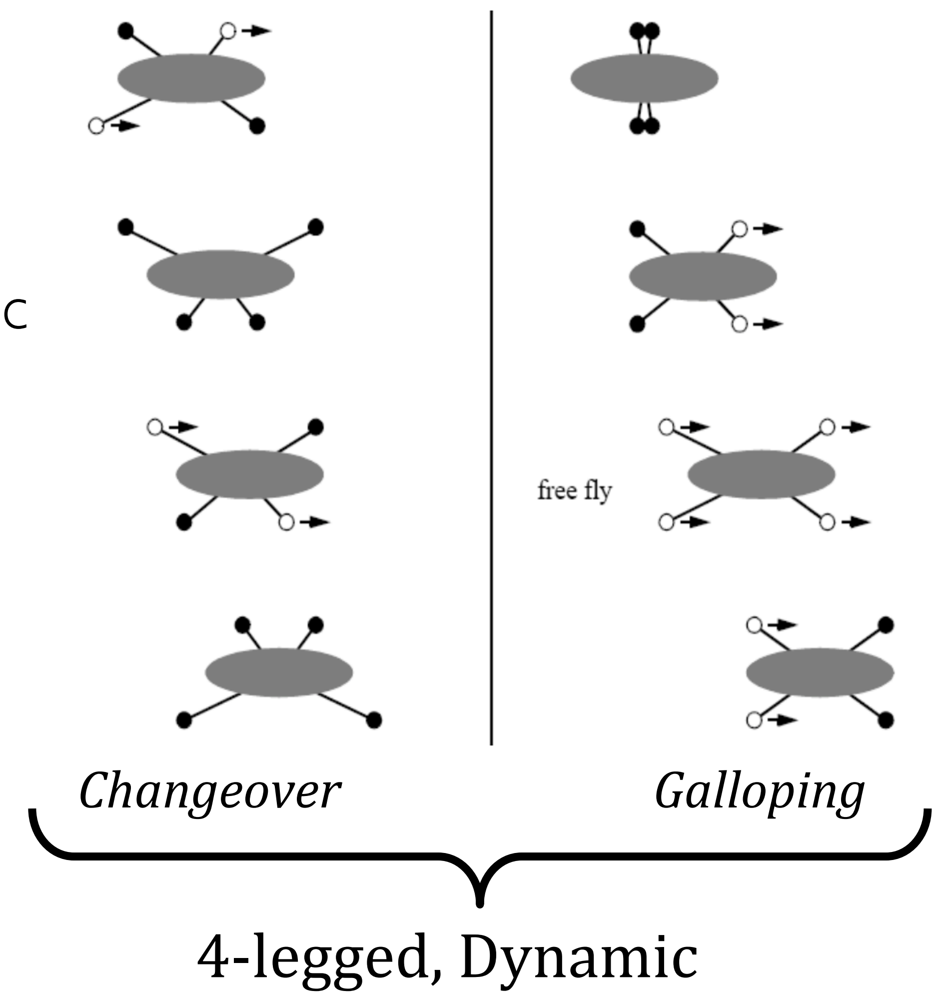
- Maneuverability vs Control
- Wheels and Wheel Arrangements
- Walking vs. Rolling vs. Other
- Flying
  - Scaling and Lift
- Other: snake movement, jumping, …

Mobility: Terminology

- Degrees of Freedom
- Compliance
  - *Give* when pushed back on
  - Related to safety
- Slip
  - Motor slip: motor turns, joint doesn't move
  - Locomotive slip: slipping/skidding on floor
- Back-drive
  - Whether it breaks when moved in reverse
  - Different from compliance

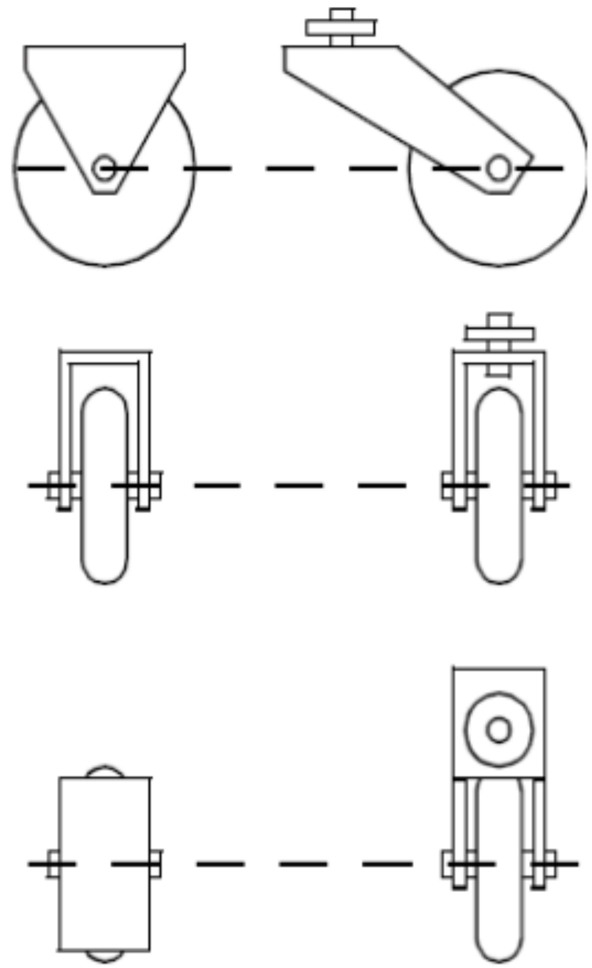
Mobility: Legged

- Gaits
  - What is a gait? Sequence of feet up and down
  - Static (always stable), dynamic (stable while moving)
- Walking
- Constructions (How many legs? Why?)
- Active vs Passive Walking



Mobility: Rolling

- Types of wheels
  - Standard
  - Castor
  - Omni (several types)

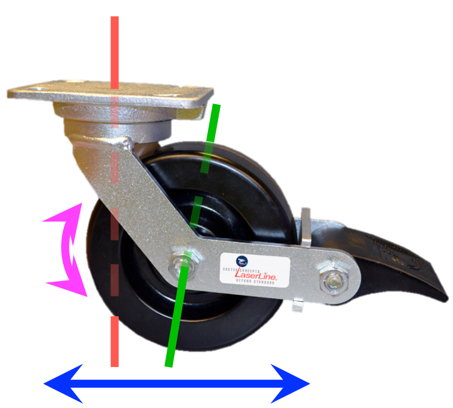


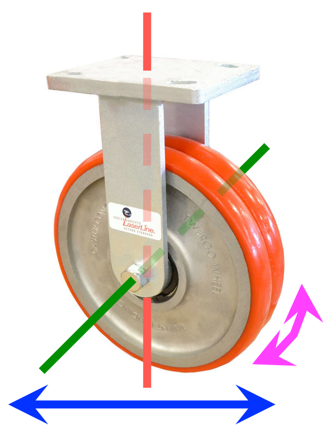
Mounting axis

Axle

Direction of rotation

Direction of translation





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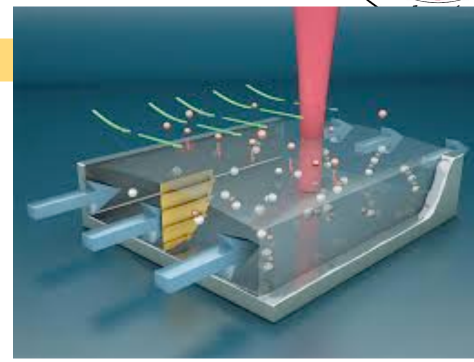
Sensors

- Perceive the world
  - **Passive sensors** capture signals generated by environment.
    - Background, lower power. E.G.: cameras.
  - **Active sensors** probe the environment. Explicitly triggered,
    - More info, higher power consumption. Example: lidar
- What are they sensing?
  - The **environment**: e.g. range finders, obstacle detection
  - The robot's **location**: e.g., gps, wireless stations
  - Robot's **internals**: joint encoders
- Proprioception: internal state

Some Typical Sensors

- Optical
  - Laser, 3D, RGB(D)
- Pressure, temperature, chemical
- Motion & Accelerometer
- Acoustic
  - Sonar, ultrasonic
- E-field Sensing
- Range-finding
- Encoders



Sensors: Characterization

Types of Sensors:

- Active / Passive
- Proprioceptive / Exteroceptive
- Incremental / Absolute

Characteristics of Sensors:

- Range
- Resolution
- Dynamic Range
- Linearity
- Bandwidth
- Sensitivity

Sensors: Error

- Precision and Recall
- Accuracy
- Systematic error → deterministic failures
  - Caused by factors that can (in theory) be modeled
  - Can it be calibrated out?
- Random error → non-deterministic failures
  - No modeling or prediction possible
  - However, can be *described* probabilistically

Sensors: Error and Accuracy

- Error
  - Difference between sensor output and true value

$$error = m - v \quad \begin{cases} m = \text{measured value} \\ v = \text{true value} \end{cases}$$

- Accuracy: unitless measure

error

$$\left(accuracy = 1 - \frac{|m - v|}{v} \right)$$

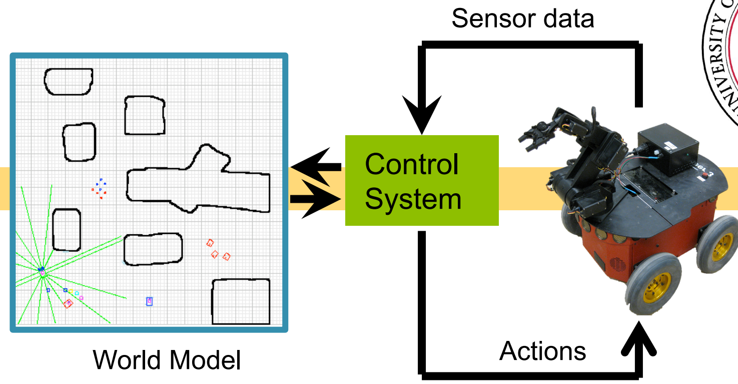
Precision (But Not Recall)

- Precision
  - Reproducibility of sensor results
- A distribution of error can be characterized by:
  - Mean error: μ
  - Standard deviation: σ
  - How similar are two outputs from same test?
    - Same sensor, same environment …

$$precision = \frac{range}{\sigma}$$

- Has other meanings in actuation *and* cognition

Uncertainty



- Models are imperfect!
- Probability as uncertainty
- Key: **explicit representation of uncertainty using probability theory**

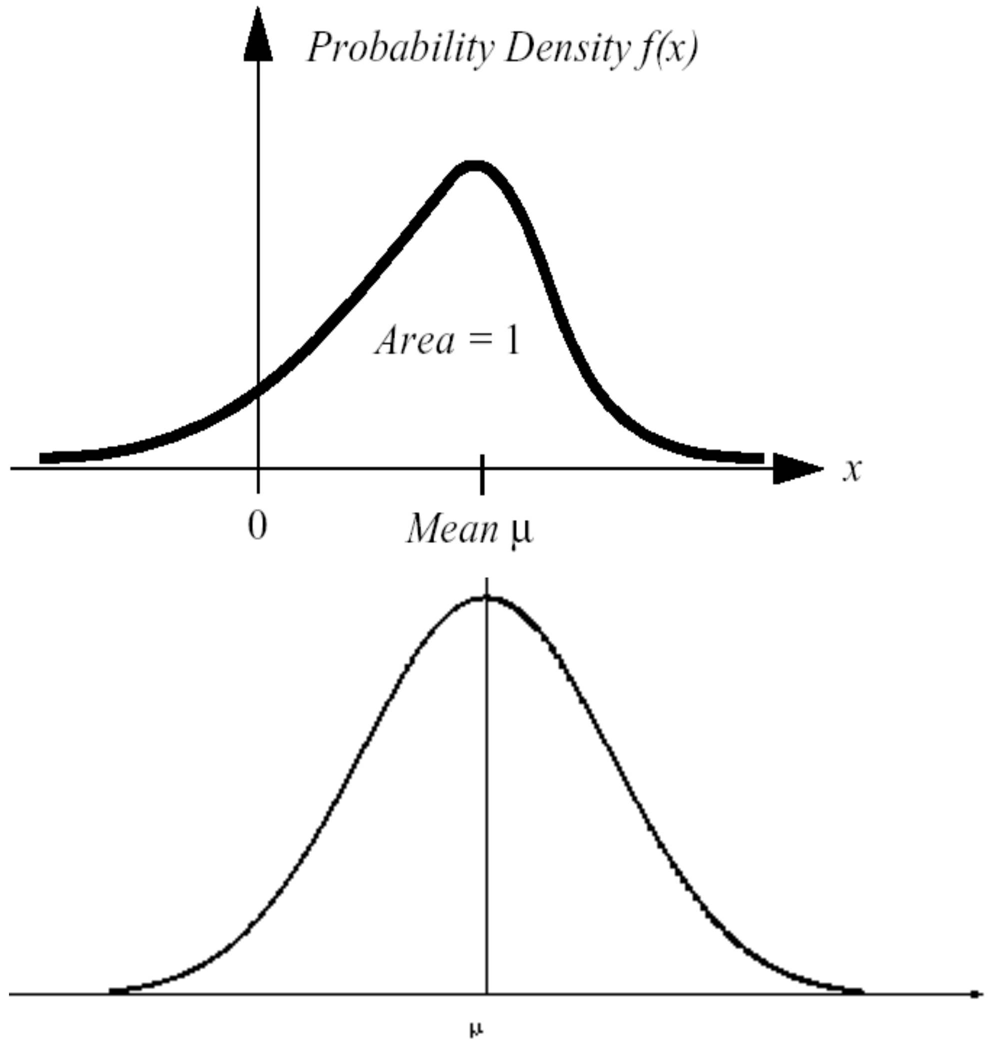
  Perception = state estimation

  Action = utility optimization

- Discrete and continuous probability
- Joint and marginal probability
- Utility functions

Error Distributions

- Simplifying assumptions:
- Zero-mean error
- Unimodal distribution
- Symmetric distribution
- Gaussian distribution

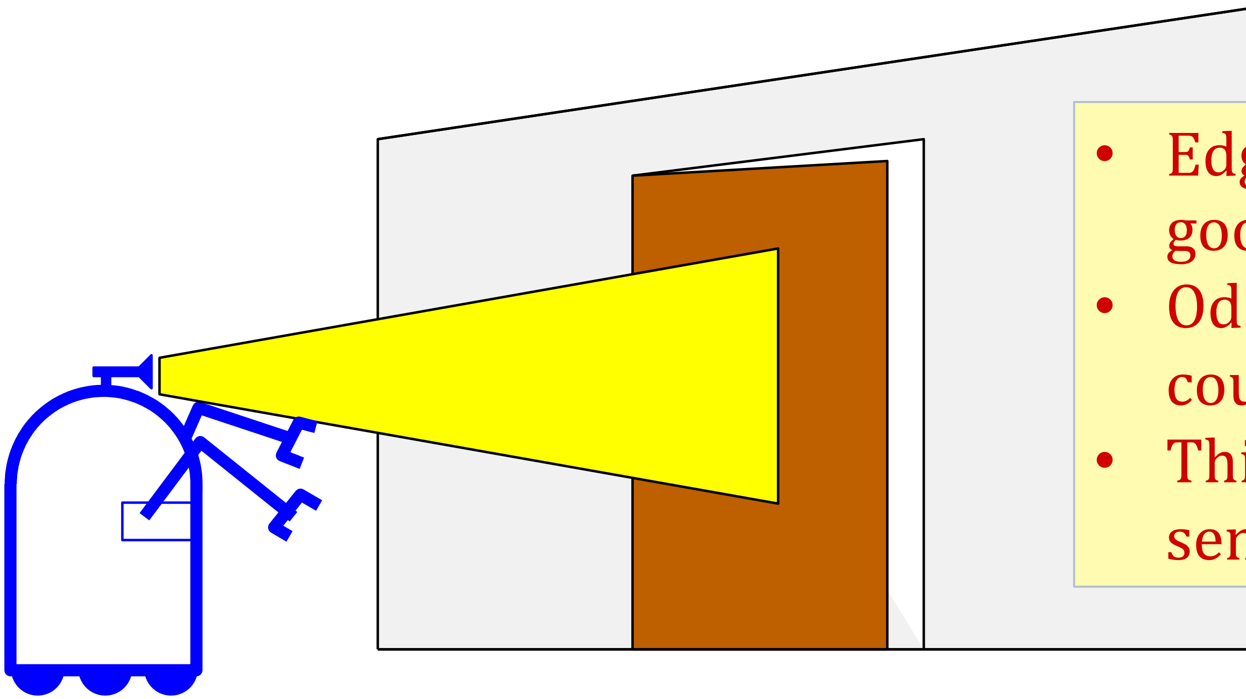


Error and Uncertainty

- What are the sources of uncertainties?
  - Blown-out camera; iffy rangefinder; skidding wheel; background noise; poor speech model; what else?
- How can uncertainties be represented / quantified
  - Deterministic vs. random error
- How do they propagate?
  - Uncertainty of a function of uncertain values?
  - How do uncertainties combine if different sensor reading are *fused*?

Example: State Estimation

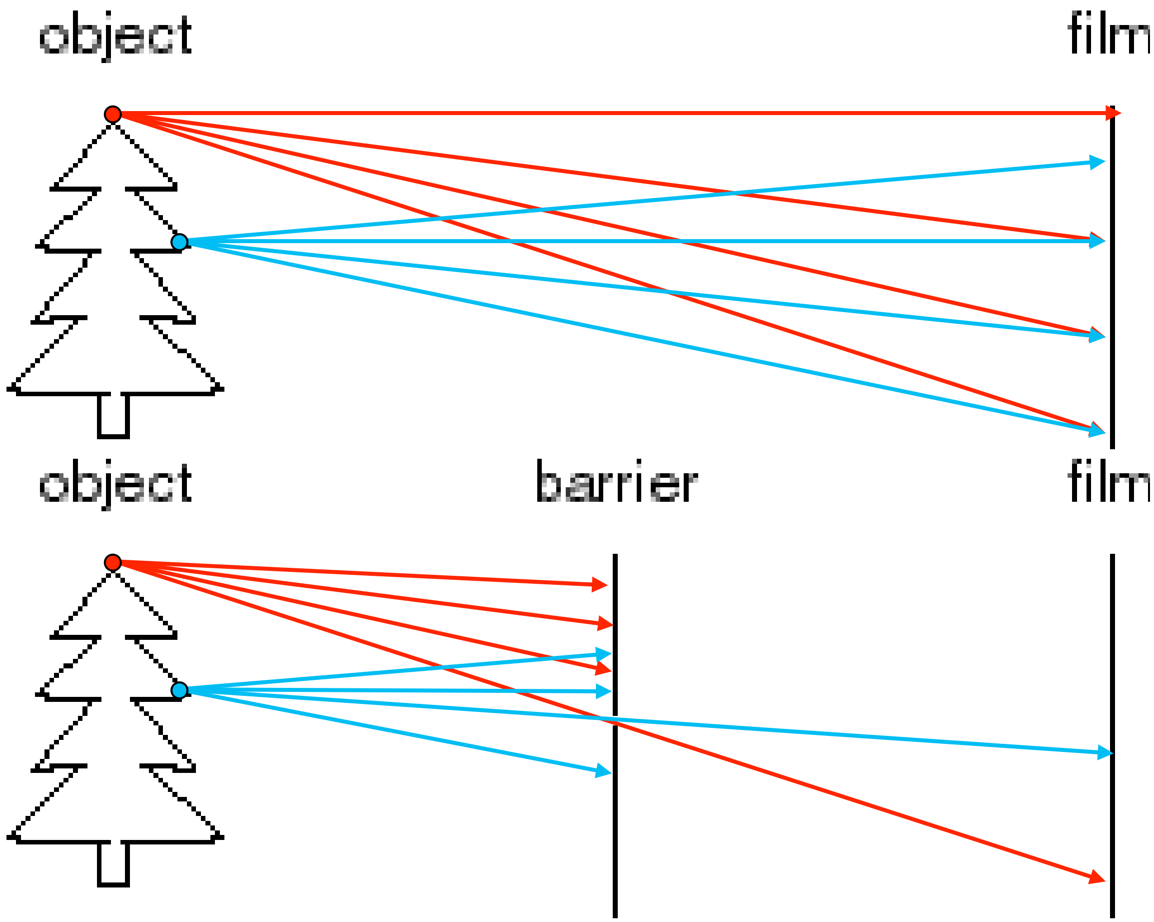
- Is the door open?
  - Camera + edge detection says the door is not at right angles
  - Odometry says I'm 2.0 meters away from door frame
  - Depth sensor says I'm 2.0 meters away from door



- Edge detection pretty good indoors?
- Odometry very noisy; could be off by 20cm.
- This specific depth sensor is very good

Sensors: Vision

- How does a camera work?



Range (Distance) Sensors

- Range sensors – how far is robot from something?
  - Key element for localization and environment modeling
- Stereo
  - Humans; Bumblebee/Bb2
- Time-of-Flight
  - Laser
  - Sonar
  - Kinect 2
- Structured Light
  - Kinect

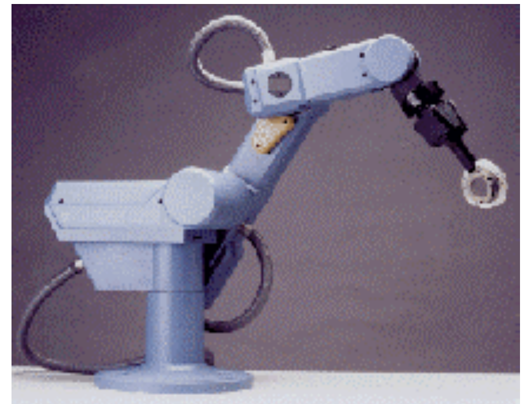
Active

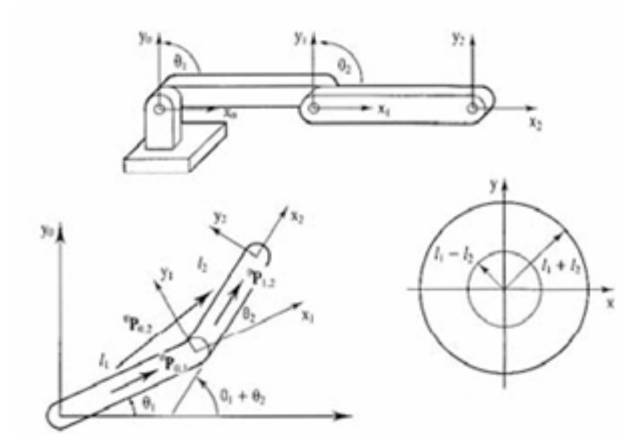
Actuators

- Take some kind of action in the world
  - Involve movement of robot or subcomponent of robot
- Robot actions can include?
  - Pick and place: Move items between points
  - Path control: Move along a programmable path
  - Sensory: Employ sensors for feedback (e-field sensing)
  - Manipulation: interact with objects in the world

Some Typical Actuators

- Pneumatic
- Hydraulic
- Electric solenoid
- Motors
  - Definitely know this one.

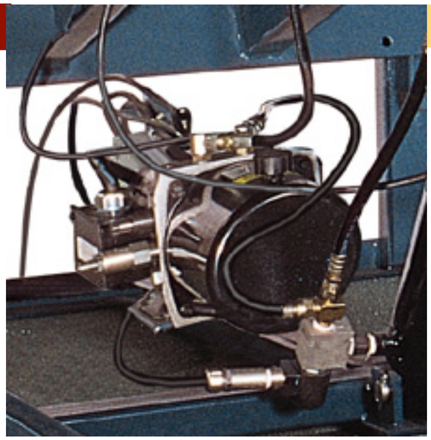




Manipulation

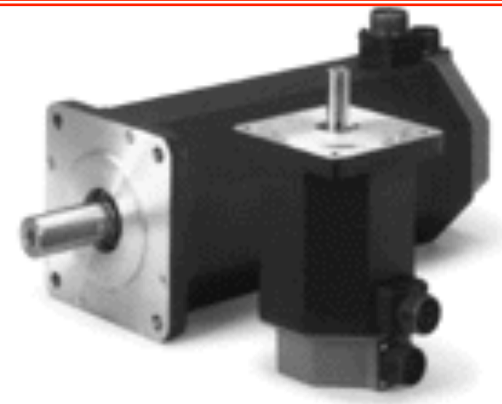
- What is a manipulator?
  - Manipulates something in the world
  - Directly or indirectly
- What kinds exist?
  - Realistically it's:
    - Grippers
    - Other

Actuators



Hydraulic Motor

Pneumatic Cylinder



Stepper Motor

Pneumatic Motor

DC Motor

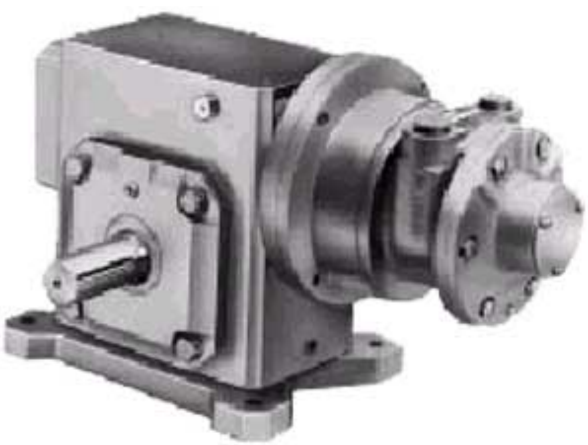
Servo Motor

Motors

- Should know now how these work!
- What is a motor?
  - Basic idea: electricity goes in, rotation happens.
  - Rotation is really useful!

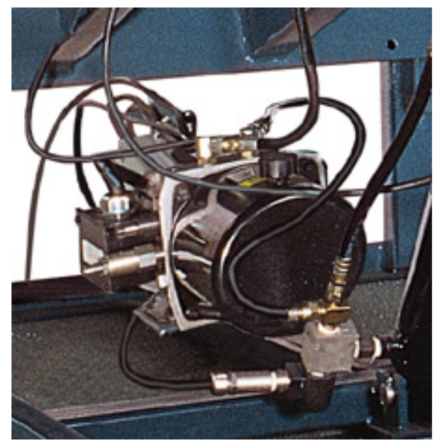
Other Choices

- Hydraulic/pneumatic
  - Heavy loads, high speeds
  - Sometimes hard to control (esp. pneumatic)
  - Doesn't produce sparks



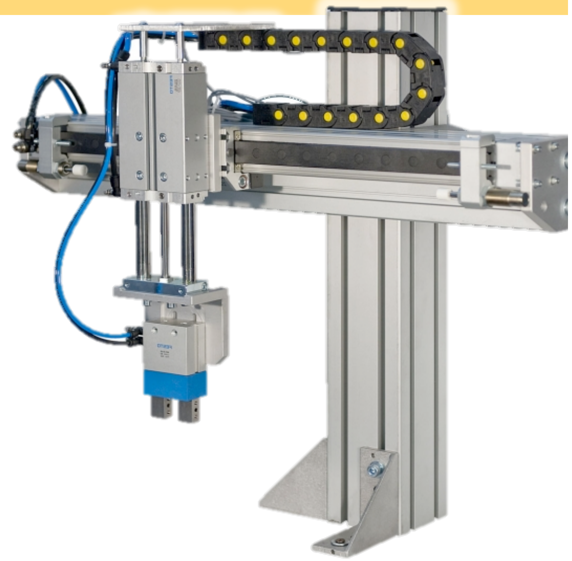
Pneumatic Motor

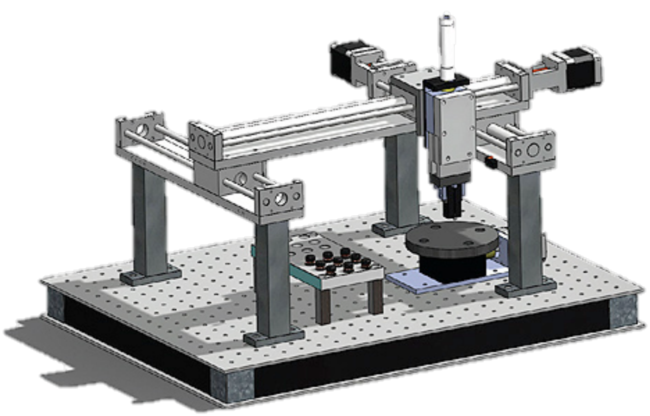
Pneumatic Cylinder

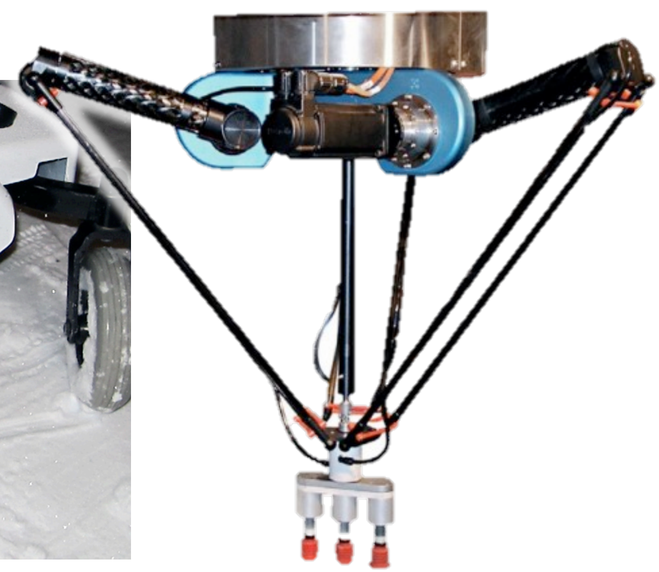


Hydraulic Motor

Manipulators





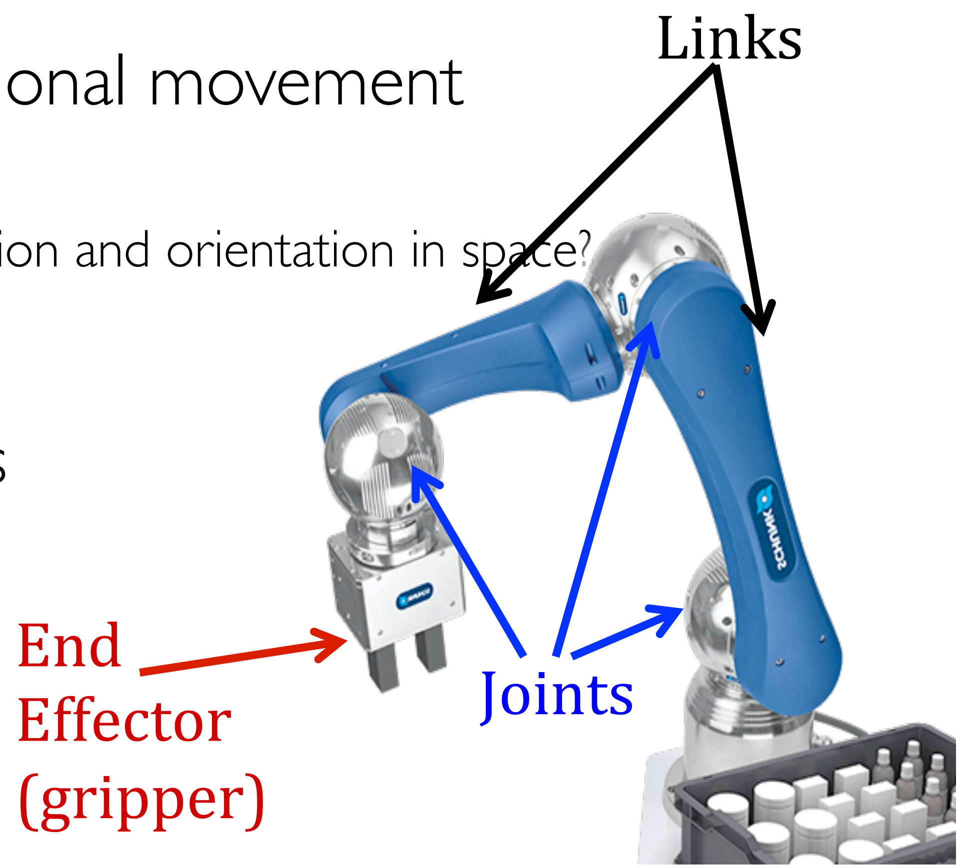


Terminology

- Actuator
  - Generates motion or force; usually a motor
  - "Drive type"
- Actuation
  - How are the individual parts made to move?
- End Effector
  - Device at the end of an arm; interacts with environment
- DoFs
- Gripper

Manipulator Robot

- Modeled as a chain of *rigid links* connected by *joints*
- Links: unjointed length of robot
- Joints: translational or rotational movement
  - Joints have DoFs
    - How many to describe its position and orientation in space?
  - Sliding or jointed
- Manipulator / End Effectors
  - Grippers / Tools
  - Sensors

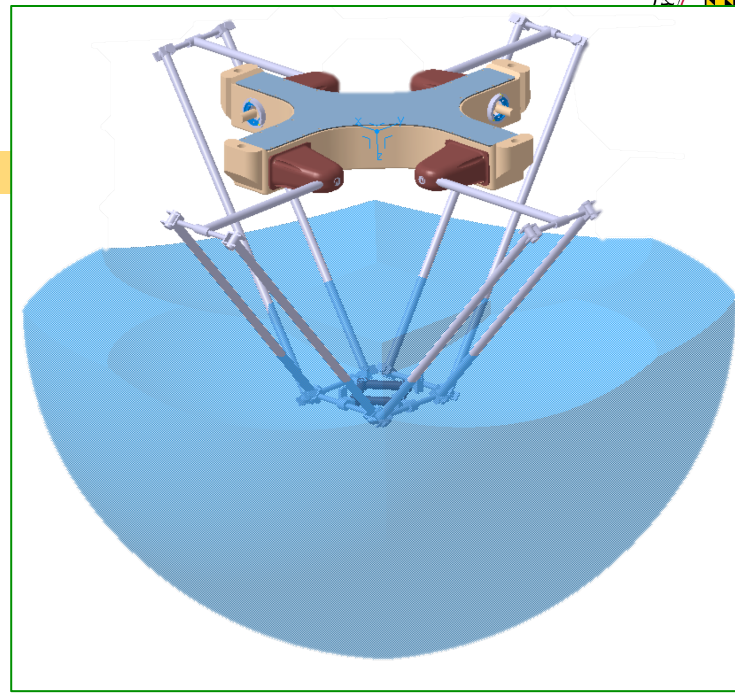


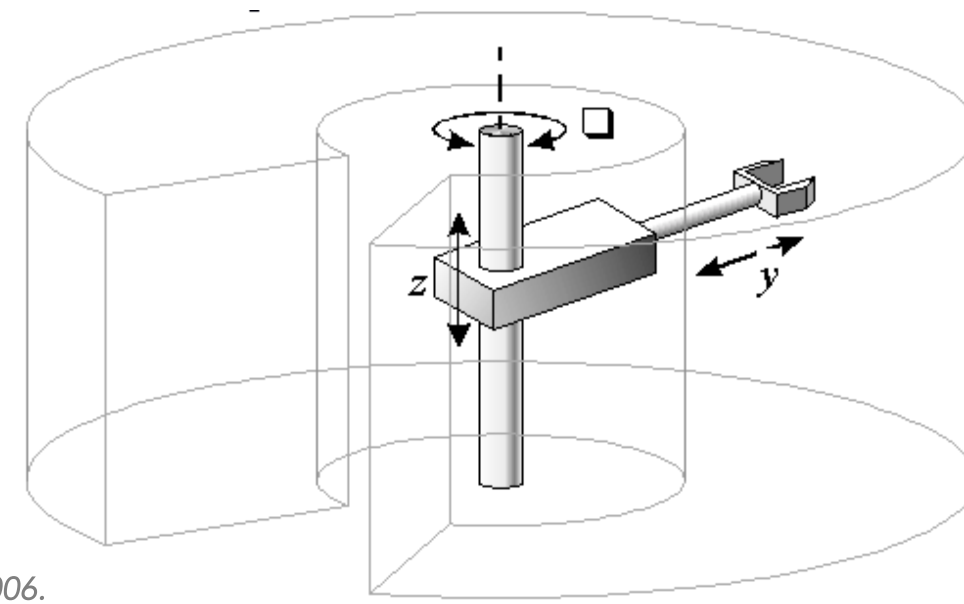
Characterization

- By drive
- By actuation
  - Tendons
  - Direct servoing
  - Underactuation
- By motion
  - Prismatic (linear)
  - Revolute (rotational)
- By Characteristics
  - Payload
  - Working area/radius

Workspaces

- Configuration provides *geometry*
- Workspace
  - Set of all possible *positions* of end effector
- Dexterous workspace
  - Set of points where end effector can be any orientation

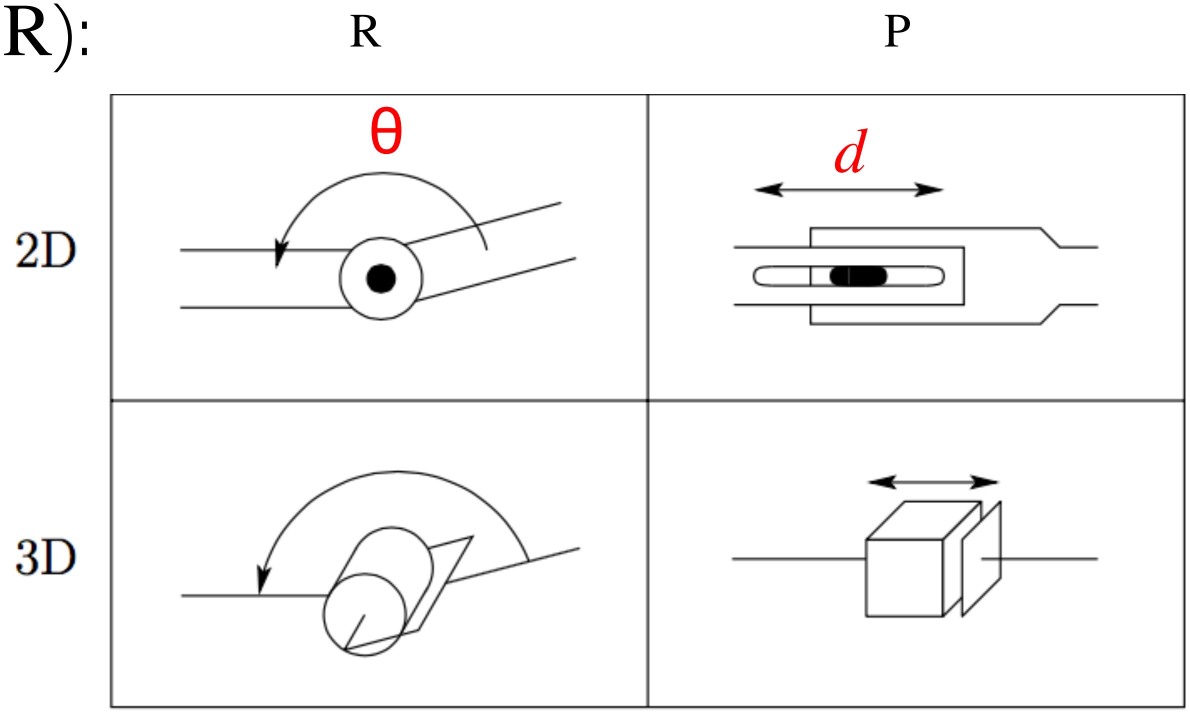




Spong, Hutchinson, Vidyasagar. Robot Modeling and Control. 2006.
engineerjau.wordpress.com/2013/07/07/on-the-basis-of-workspaces-of-robotic-manipulators-part-1

Joints, P(rismatic) & R(evolute)

- *Prismatic* (denoted **P**): sliding / translational / linear; allows a linear relative motion between 2 links
- *Revolute* (denoted **R**): Rotational; allows relative rotation between two links
- Combinations of these describe arm *configuration*

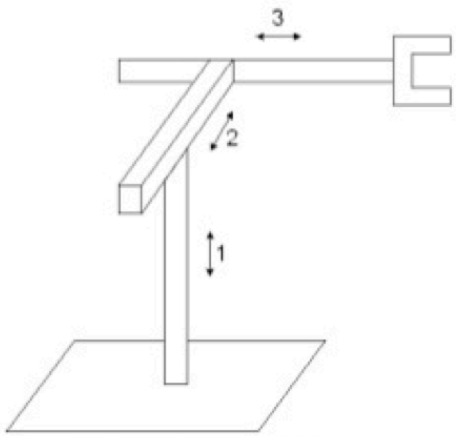


- All possible configurations = *configuration space*

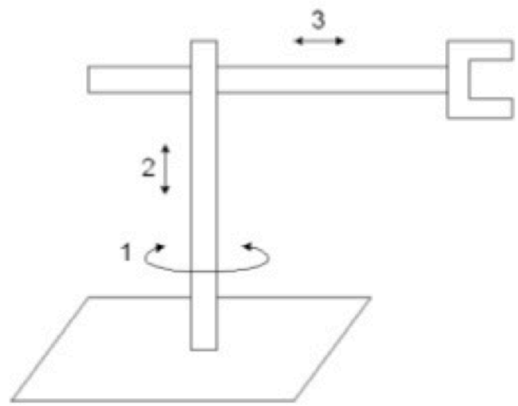
Spong, Hutchinson, Vidyasagar. Robot Modeling and Control. 2006.

Configurations

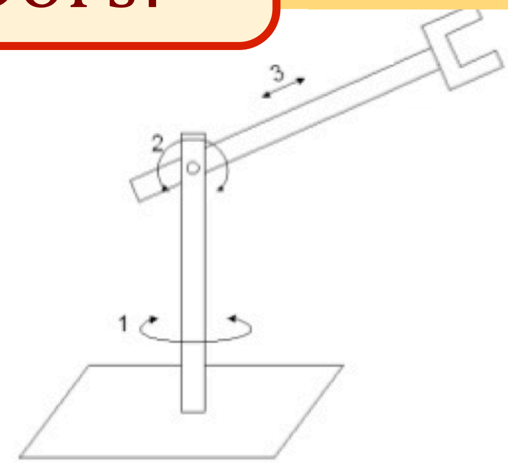
How many DOFs?



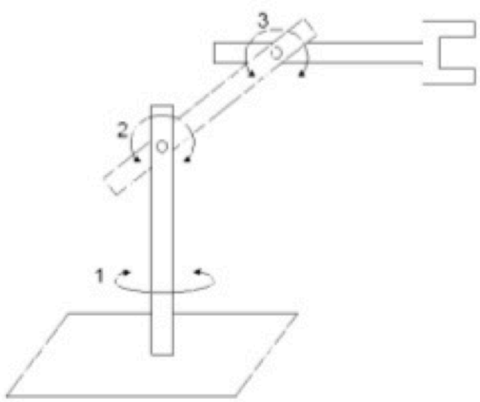
Cartesian: PPP



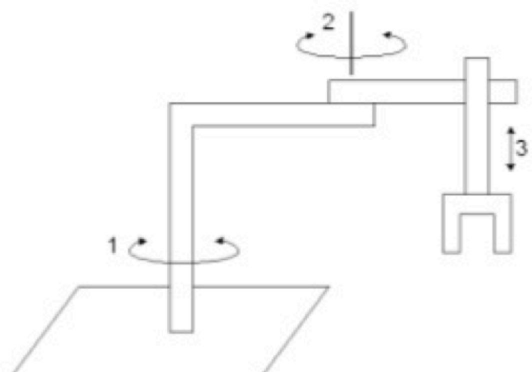
Cylindrical: RPP



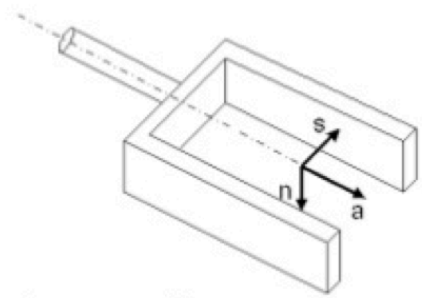
Spherical: RRP



Articulated: RRR



SCARA: RRP



Hand coordinate:

n: normal vector; **s**: sliding vector;

a: approach vector

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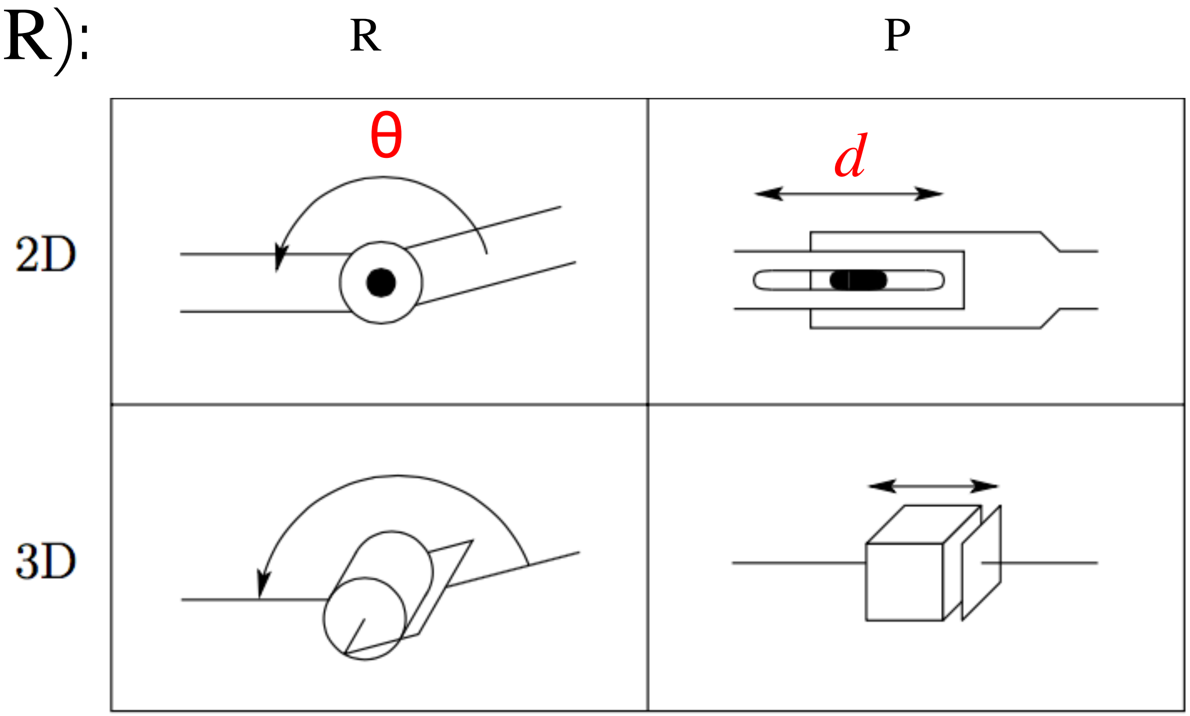

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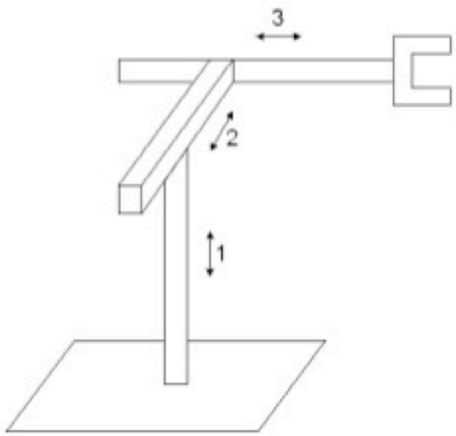

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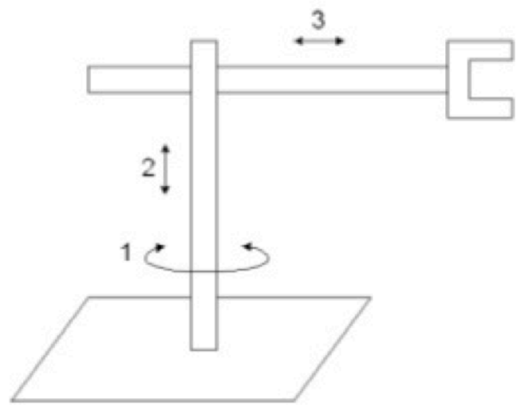
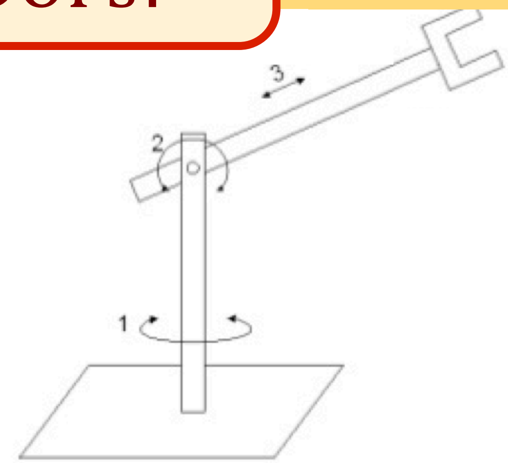
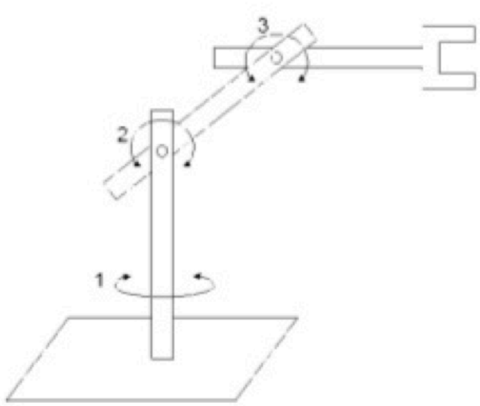


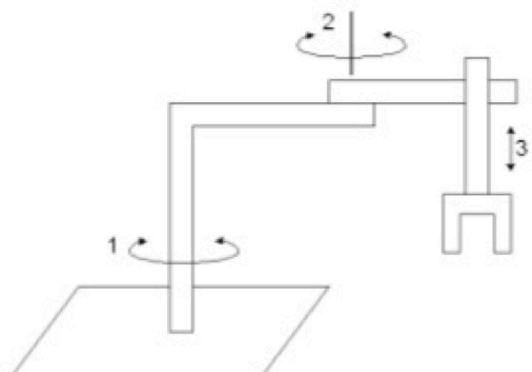
Cylindrical: RPP



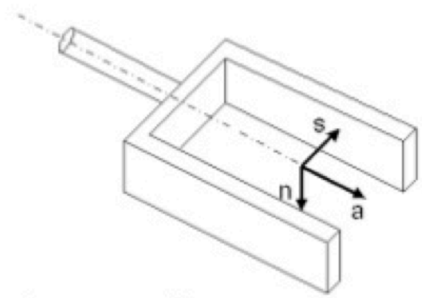
Spherical: RRP



Articulated: RRR



SCARA: RRP



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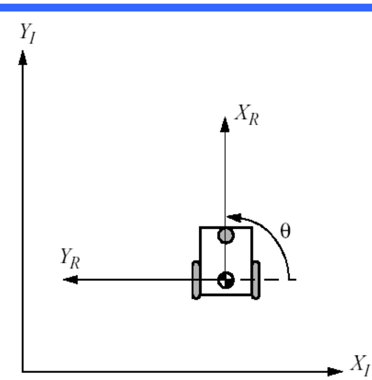
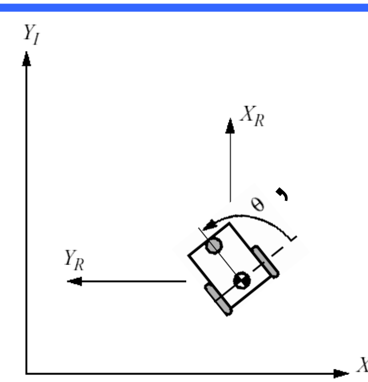
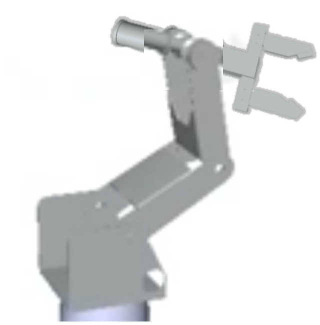
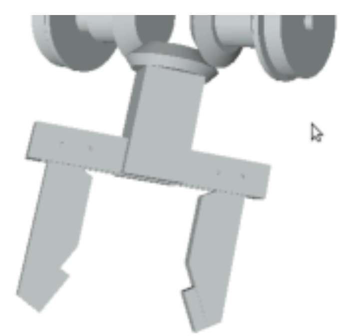
Kinematics

- What is kinematics?
  1. The study of the **motion of objects.**
  2. The study of the geometrically possible motion of a body or system of bodies without consideration of the causes and effects of the motions

- Movement determines the (eventual) position and orientation of the robot
  - Mobile: position and orientation wrt. an arbitrary initial frame
  - Manipulator: position and orientation of end effector*

- Where are we? How did we get there?

Kinematics: Position and Orientation

	Where is it?	What's its orientation?
Mobile	On an $\{x,y\}$ plane 	Heading θ 
Manipulator	In some $\{x,y,z\}$ space 	$\{r/p/y\}$ of end effector 

Mobile Kinematics

- Kinematics:
  - Geometrically possible motion of a body or system of bodies without consideration of the causes and effects of the motions
- For mobile robots: position and orientation

  - Kinematics:
    - I moved this way. Where am I and where am I pointed?
  - Inverse Kinematics (IK):
    - I'm here, pointed this way. What motions got me there?
    - I want to be here pointed this way. What motions should I make?
- Position and orientation wrt. an arbitrary initial frame

Mobile Position & Orientation

Frames of reference:

- $\{X_I, Y_I\}$: Global
- $\{X_R, Y_R\}$: Robot

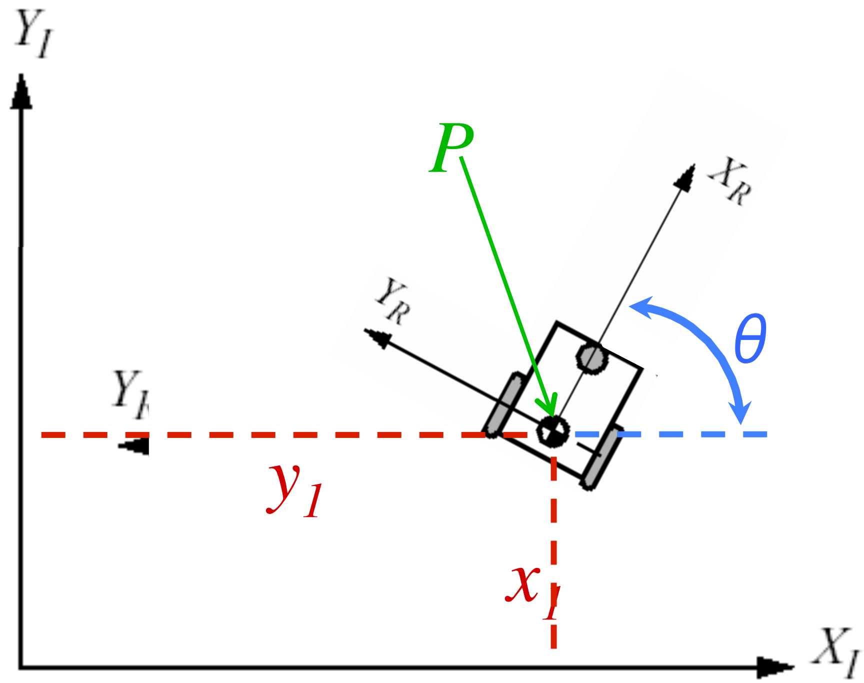
Robot: point P

Position (of P):

- $\{x_{I,1}, y_{I,1}\}$

Heading:

- $\{\theta\}$: I ∠ R



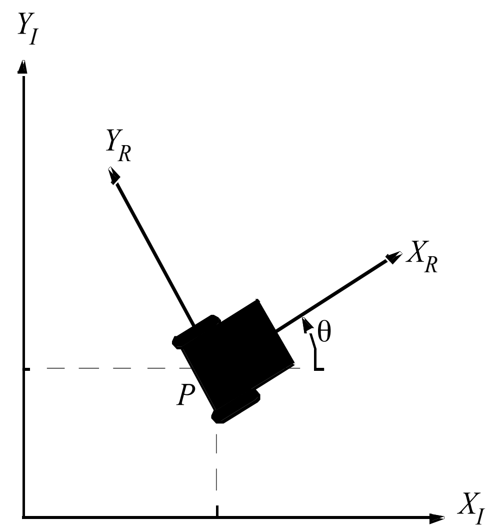
$$\xi_I = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$$

Mapping Between Frames

- Global reference frame ←→ local reference frame

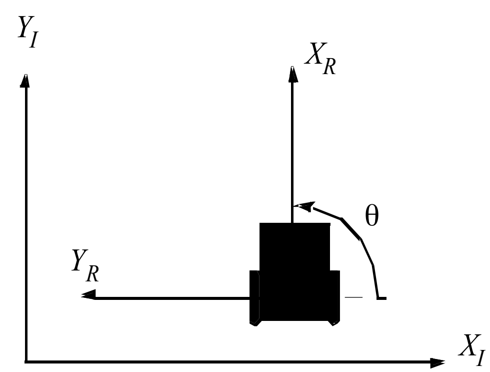
$$\{X_I, Y_I\} \leftrightarrow \{X_R, Y_R\}$$

  - Map motion from **axes** of one to **axes** of the other
    - This mapping depends on current pose



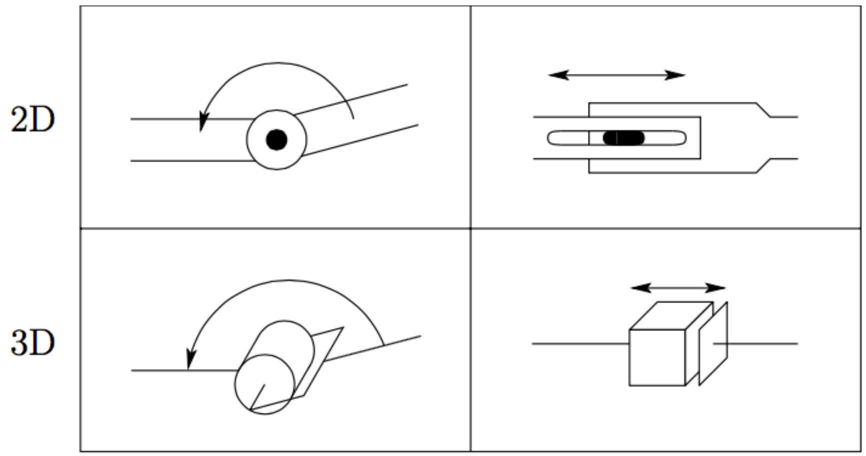
- Use *orthogonal reference frame*:

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



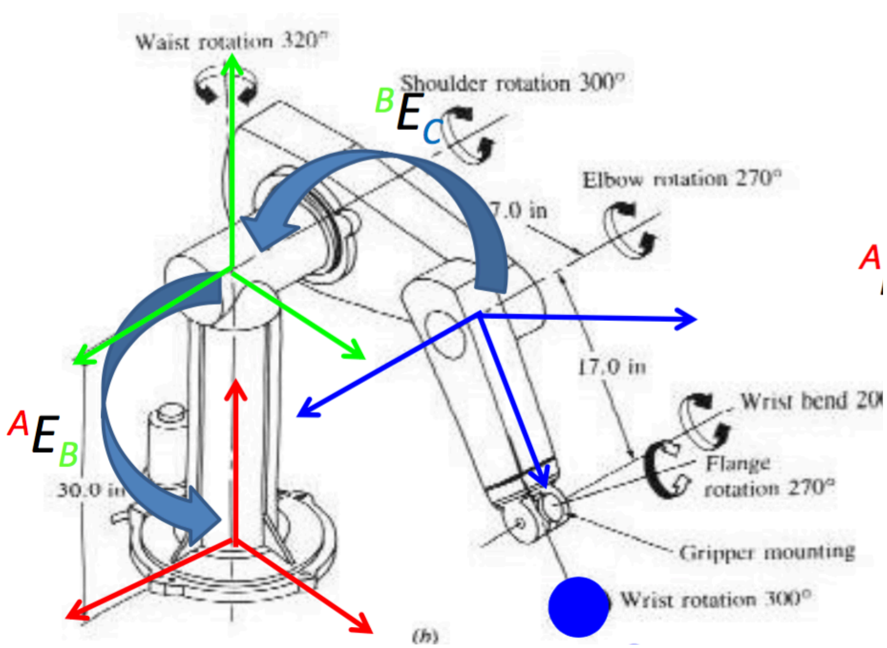
Manipulator Kinematics

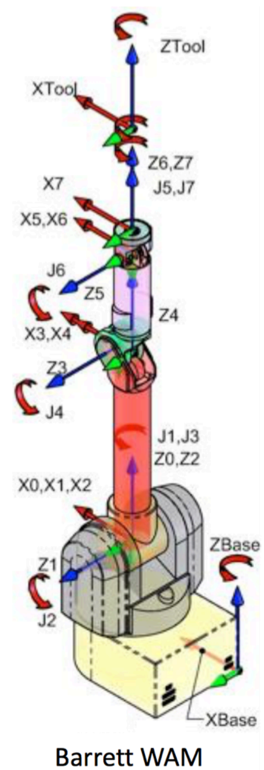
- Kinematics:
  - Geometrically possible motion of a body or system of bodies
- For <u>manipulator</u> robots
  - End effector position and orientation, wrt. an arbitrary initial frame
- A manipulator is moved by changing its…
  - Joints: revolute and prismatic

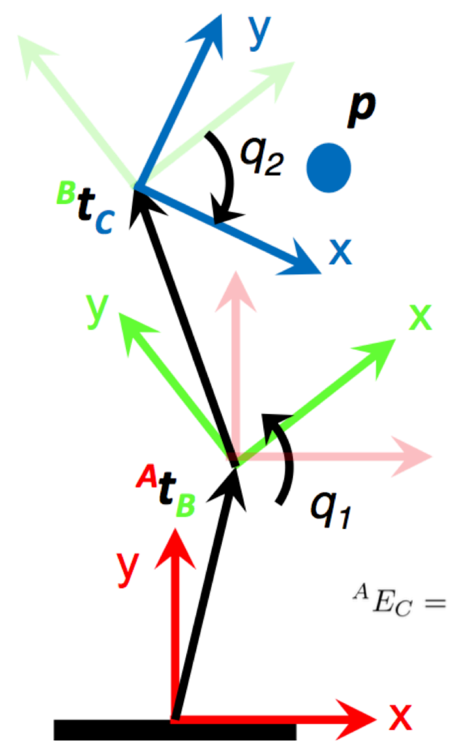


Multiframe Kinematics

- How many frames of reference do we have?
  - We've been translating among frames based on possible motion
- How do they relate?

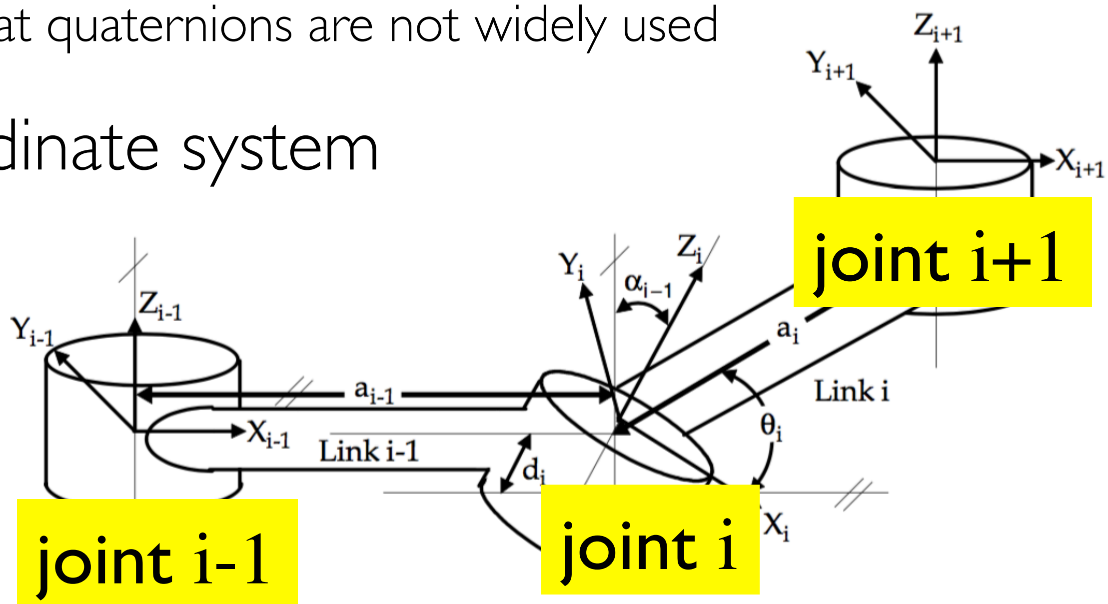




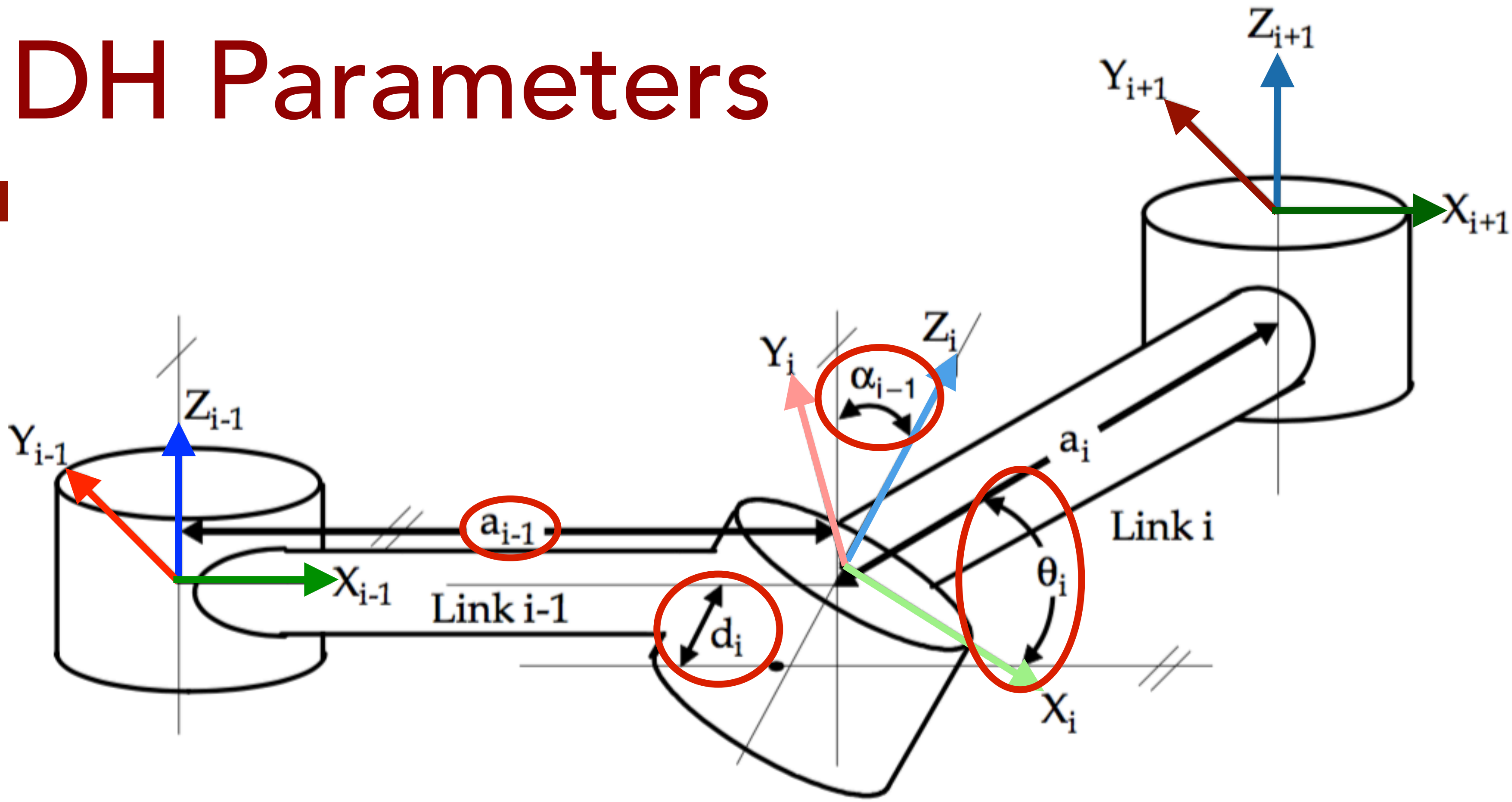


Describing A Manipulator

- Arm made up of links in a chain
  - How to describe each link?
  - Many choices exist
  - DH parameters widely used
    - Although it's not true that quaternions are not widely used
- Joints each have coordinate system
  - {x,y,z}, r/p/y — *OR!!*
- *DH parameters*
  - Denavit-Hartenberg
  - $a_{i-1}, \alpha_{i-1}, d_i, \theta_2$



DH Parameters



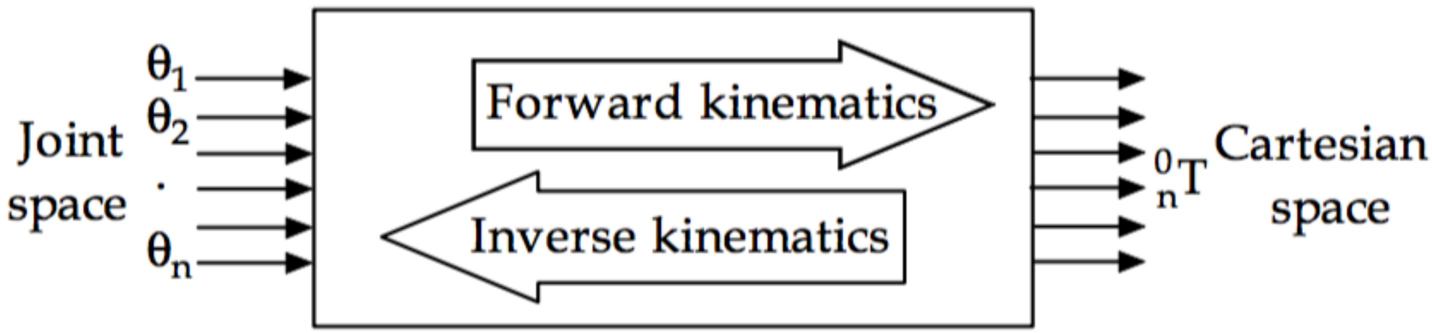
a_{i-1} : link length – distance Z_{i-1} and Z_i along X_i

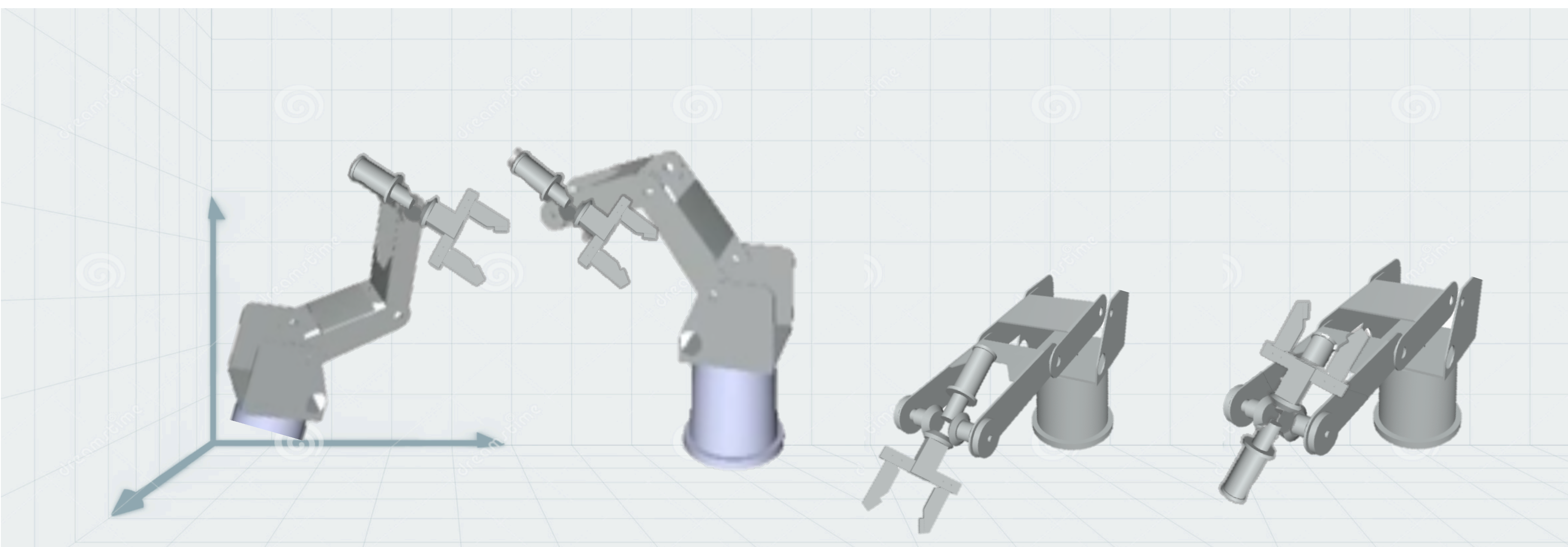
α_{i-1} : link twist – angle Z_{i-1} and Z_i around X_i

d_i : link offset – distance X_{i-1} to X_i along Z_i

θ_2 : joint angle – angle X_{i-1} and X_i around Z_i

Forward Kinematics & IK



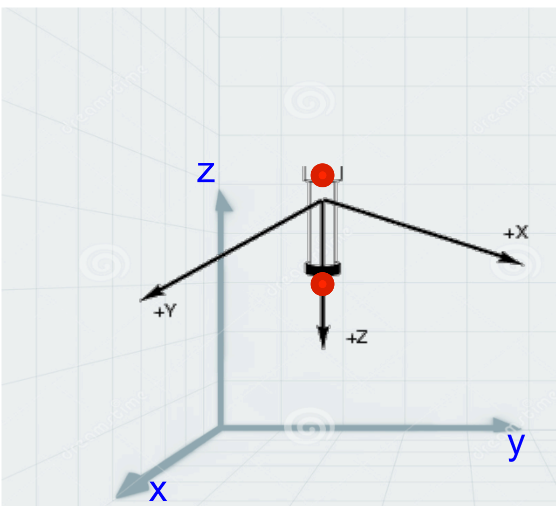


Analytical vs. Numerical

- One major way to classify IK-solving approaches: **analytical** vs **numerical** methods
- Analytical
  - Find an exact solution by directly inverting the forward kinematics equations.
  - Works on relatively simple chains.
- Numerical
  - Use approximation and iteration to converge on a solution.
  - More expensive, more general purpose.
- We will look at one technique: Jacobians

Actual Goal

- Transform between robot and world coordinates
  - Why?
- Transformation of parts (points) of the robot

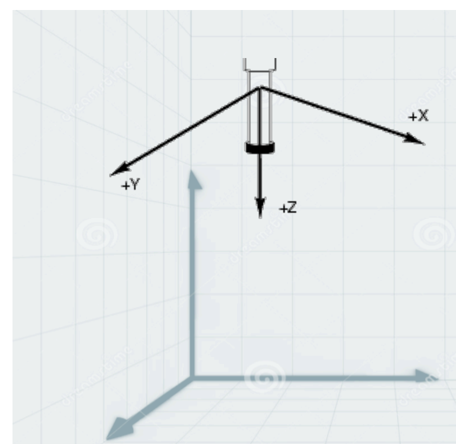


R: {0, 0, 0}
I: {4, 2, 3}

R: {0, 0, -2}
I: {4, 2, 5}

Actual Goal

- Affine transformation
  - Preserves collinearity (i.e., all points lying on a line initially still lie on a line after transformation)
  - Preserves ratios of distances (e.g., the midpoint of a line segment remains the midpoint after transformation)
- Rigid transform
  - Reflections, translations, rotations
  - Preserves internal relationship of points
    - Distances between every pair of points
    - (Remember, this is not the robot moving!)

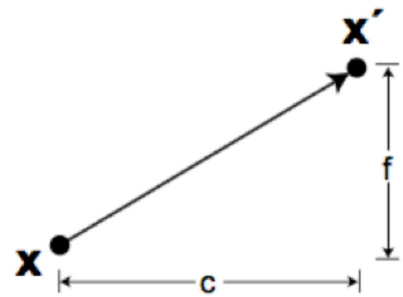


Affine Transformations

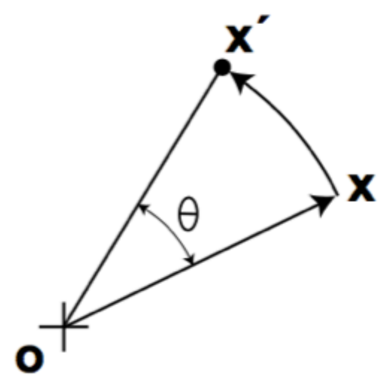
- Affine transformations:
- Given a point x (x,y), transformed x' can be written:

$$x' = \begin{bmatrix} ax + by + c \\ dx + ey + f \end{bmatrix}$$

  - Translation
  - Rotation
  - Scaling
  - Shear



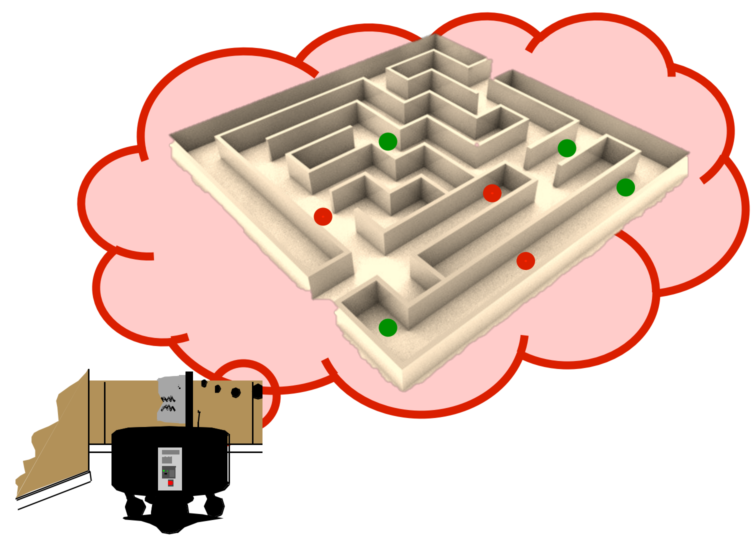
$$x' = \begin{bmatrix} x+c \\ y+f \end{bmatrix}$$



$$x' = \begin{bmatrix} x\cos\theta - y\sin\theta \\ x\sin\theta + y\cos\theta \end{bmatrix}$$

Localization: Where am I?

- Given:
  - A map (which MAY be being found on the fly)
  - A set of sensor readings
- Where am I in that map?
- Things to consider:
  - Belief representation
  - Map representation
  - Types of sensor data
  - Probabilistic representations



Challenges of Localization

- Knowing absolute position (e.g. GPS) is not sufficient
- Localization in human-scale as relates to environment
- Planning in *Cognition* needs >1 position as input
- Perception and motion plays an important role
  - Sensor noise
  - Sensor aliasing
  - Effector noise
  - Odometric position estimation
  - Probabilities and uncertainty management