- Serial manipulator - this is what our robot arm is. Think serial like serial data: one wire
- Need to understand (remember) simple vector/matrix ops
  - add
  - multiply
  - divide or inverse
  - transpose
- Process:
  - Start with a simplified version

* art skills are not important

- Euler angles, not really used here
- Example of what is called a rotation matrix
- Rotation Matrix

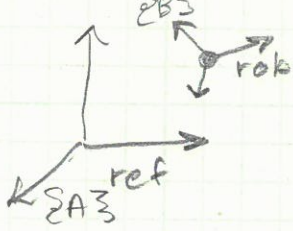
$$R^{TO}_{From} = [3\times 3] \qquad R^B_A = (R^A_B)^{-1} = (R^A_B)^T$$

look Ma' no inversion

- Position + Orientation

* properties of orthonormal

pose: common robotics term for the combined position/orientation of something (robot) relative to a reference frame.



{X} ≡ reference frame name, here it is X

$$P^A = R^A_B P^B$$

P^B ← in ref {B}

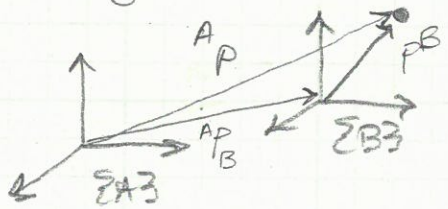
R^A_B ← transition from {B} to {A}

P^A ← values in {A}

P^A ≡ vector measured in ref {A}

P^ω ≡ vector measured in ref {ω}

- Adding 2 Frames together



$^A p_B \equiv \{B\}$ location in $\{A\}$, this is called a translation

Now what we want is p^A, where is the dot in $\{A\}$.

$$p^A = {}^A p_B + {}^A_B R \, p^B$$

translation; rotation, to align $\{B\}$ with $\{A\}$

* you can not add $^A p_B$ and p^B together, they are defined in different frames

- To be more compact, we will use a homogenious matrix

$$T^A_B = \begin{bmatrix} R^A_B & p^A_B \\ 0\ 0\ 0 & 1 \end{bmatrix} \Leftarrow 4 \times 4$$

$R^A_B \equiv 3 \times 3$ matrix

$p^A_B \equiv 3 \times 1$ vector

bottom row is always $[0\ 0\ 0\ 1]$ This will mean something when we get to vision

$$p^A = T^A_B \, p^B$$

- You can also these together:

$$T^A_C = T^A_B * T^B_C \quad \text{think} \Longrightarrow \quad T^A_{\cancel{B}} * T^{\cancel{B}}_C = T^A_C$$

(they cancle)

T^A_B: $\{B\} \to \{A\}$; T^B_C: $\{C\} \to \{B\}$

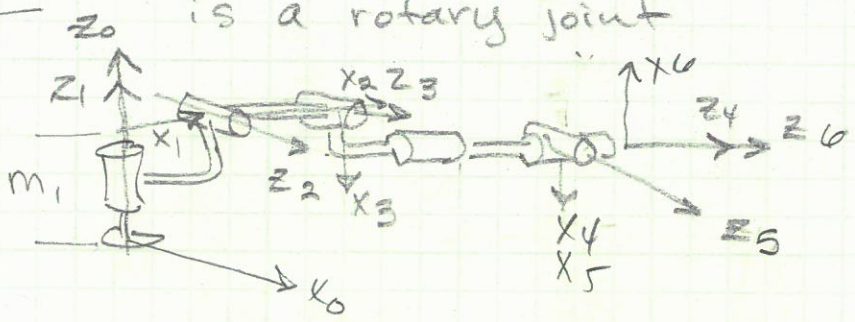
- DH
  - I suggest you read and follow the examples

- DH Process (my summary)

① Put Z-axis through axis of rotation

② Put X-axis along the common perpendicular between the Z-axes

③ Starting @ 0, assign each frame a number
- $\{0\}$ is the base reference frame which generally doesn't move
- $\{1\}$ is often co-aligned w/ $\{0\}$ if it is a rotary joint



$X_4 \equiv Z_4 \perp Z_5$, X_4 @ intersection

$X_5 \equiv Z_5 \perp Z_6$, X_5 @ intersection

$X_6 \equiv$ anywhere $\perp Z_6$, put @ end effector location

$X_6 \equiv Z_6$ is the last coordinate frame, pick a $\perp$ to Z_6 that is useful

	a_{i-1}	twist α_{i-1}	d_i	θ_i
1	0	0°	m_1	θ_1
2	m_2	90°	0	θ_2
3	m_3	0°	0	θ_3
4	m_5	−90	m_4	θ_4
5	0	90	0	θ_5
6	0	−90	m_6	θ_6

* I replaced d's w/ m's because it is confusing otherwise

move to end