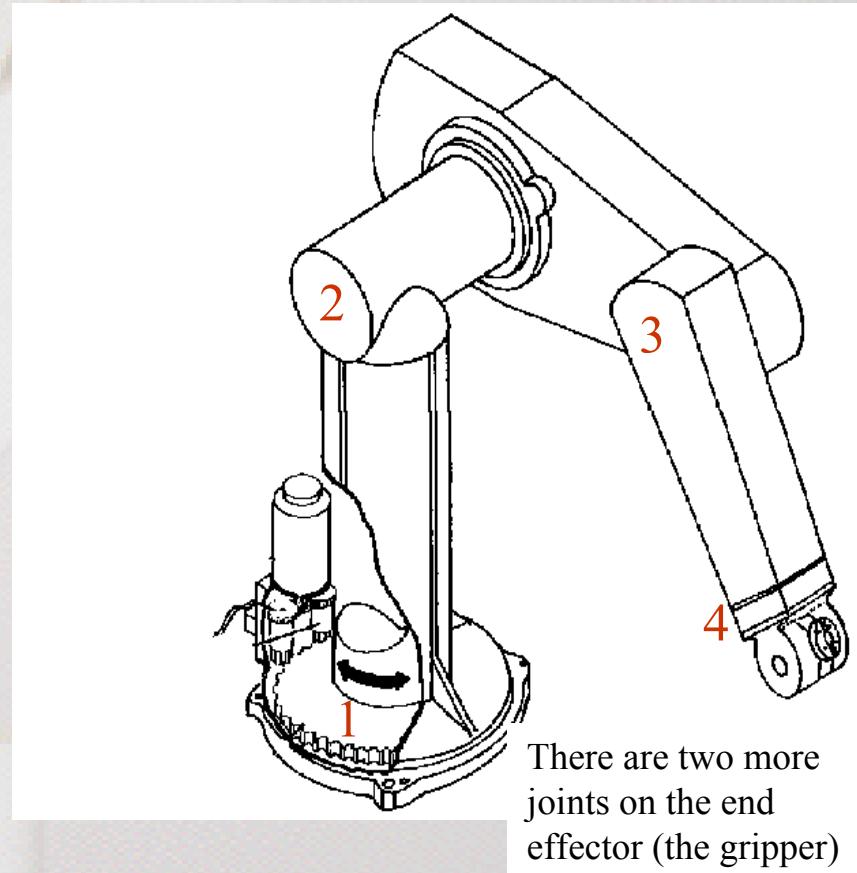
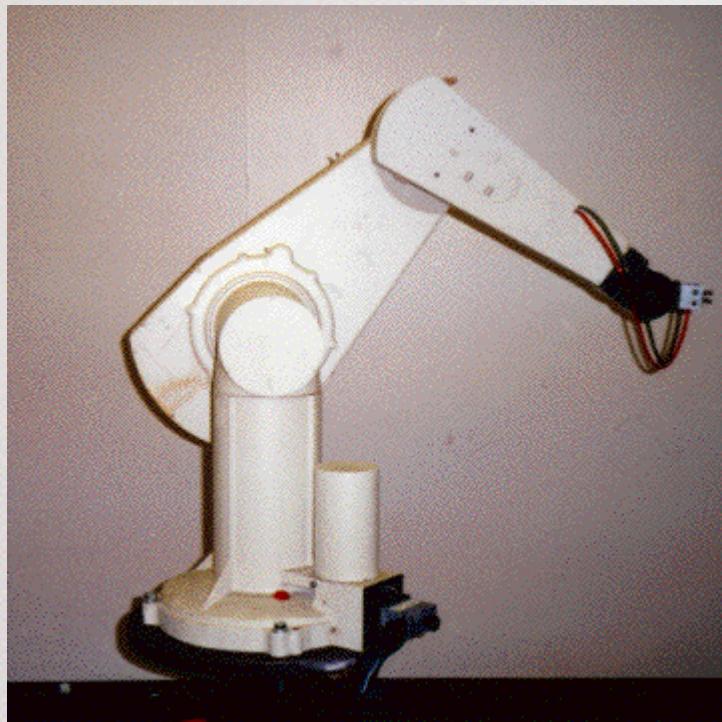


# An Introduction to Robot Kinematics

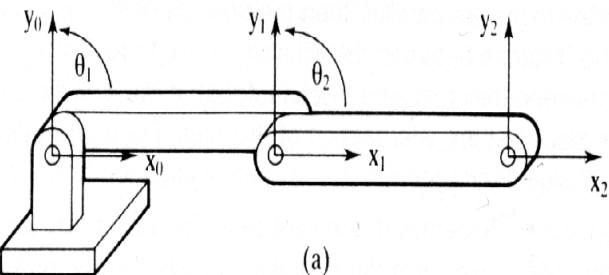
# An Example - The PUMA 560



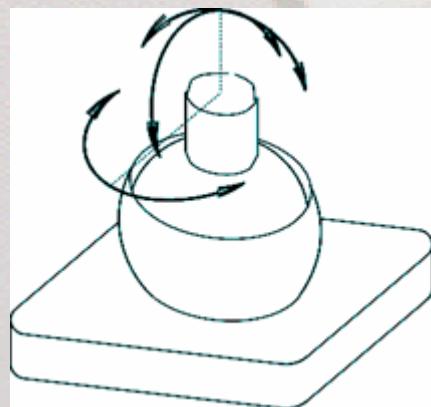
The PUMA 560 has **SIX** revolute joints

A revolute joint has **ONE** degree of freedom ( 1 DOF) that is defined by its angle

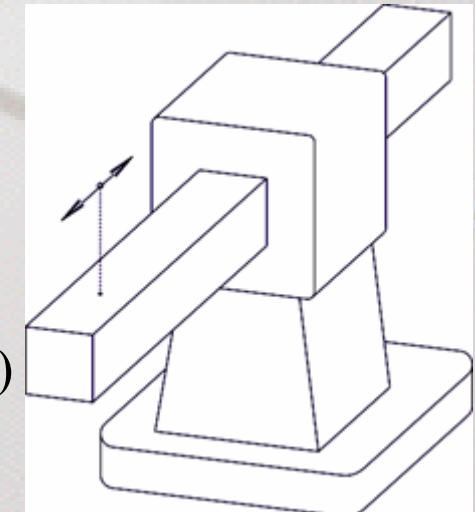
# Other basic joints



Revolute Joint  
1 DOF ( Variable - Y)



Prismatic Joint  
1 DOF (linear) (Variables - d)



Spherical Joint  
3 DOF ( Variables - Y<sub>1</sub>, Y<sub>2</sub>, Y<sub>3</sub>)

# We are interested in **two** kinematics topics

## Forward Kinematics (angles to position)

What you are given:

The length of each link  
The angle of each joint

What you can find:

The position of any point  
(i.e. it's  $(x, y, z)$  coordinates)

## Inverse Kinematics (position to angles)

What you are given:

The length of each link  
The position of some point on the robot

What you can find:

The angles of each joint needed to obtain  
that position

# Quick Math Review

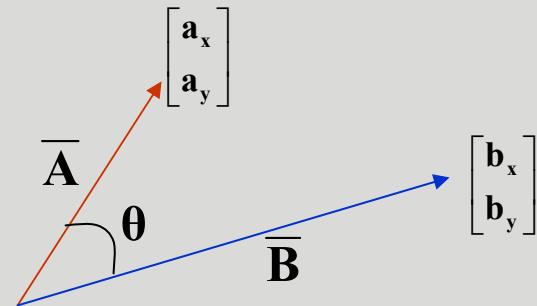
Dot Product:

Geometric Representation:

$$\overline{\mathbf{A}} \bullet \overline{\mathbf{B}} = \|\mathbf{A}\| \|\mathbf{B}\| \cos \theta$$

Matrix Representation:

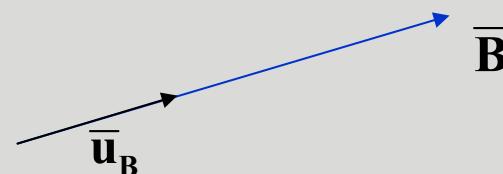
$$\overline{\mathbf{A}} \bullet \overline{\mathbf{B}} = \begin{bmatrix} \mathbf{a}_x \\ \mathbf{a}_y \end{bmatrix} \bullet \begin{bmatrix} \mathbf{b}_x \\ \mathbf{b}_y \end{bmatrix} = \mathbf{a}_x \mathbf{b}_x + \mathbf{a}_y \mathbf{b}_y$$



Unit Vector

Vector in the direction of a chosen vector but whose magnitude is 1.

$$\overline{\mathbf{u}}_B = \frac{\overline{\mathbf{B}}}{\|\mathbf{B}\|}$$



# Quick Matrix Review

## Matrix Multiplication:

An  $(m \times n)$  matrix A and an  $(n \times p)$  matrix B, can be multiplied since the number of columns of A is equal to the number of rows of B.

### Non-Commutative Multiplication

$AB$  is **NOT** equal to  $BA$

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} * \begin{bmatrix} e & f \\ g & h \end{bmatrix} = \begin{bmatrix} (ae + bg) & (af + bh) \\ (ce + dg) & (cf + dh) \end{bmatrix}$$

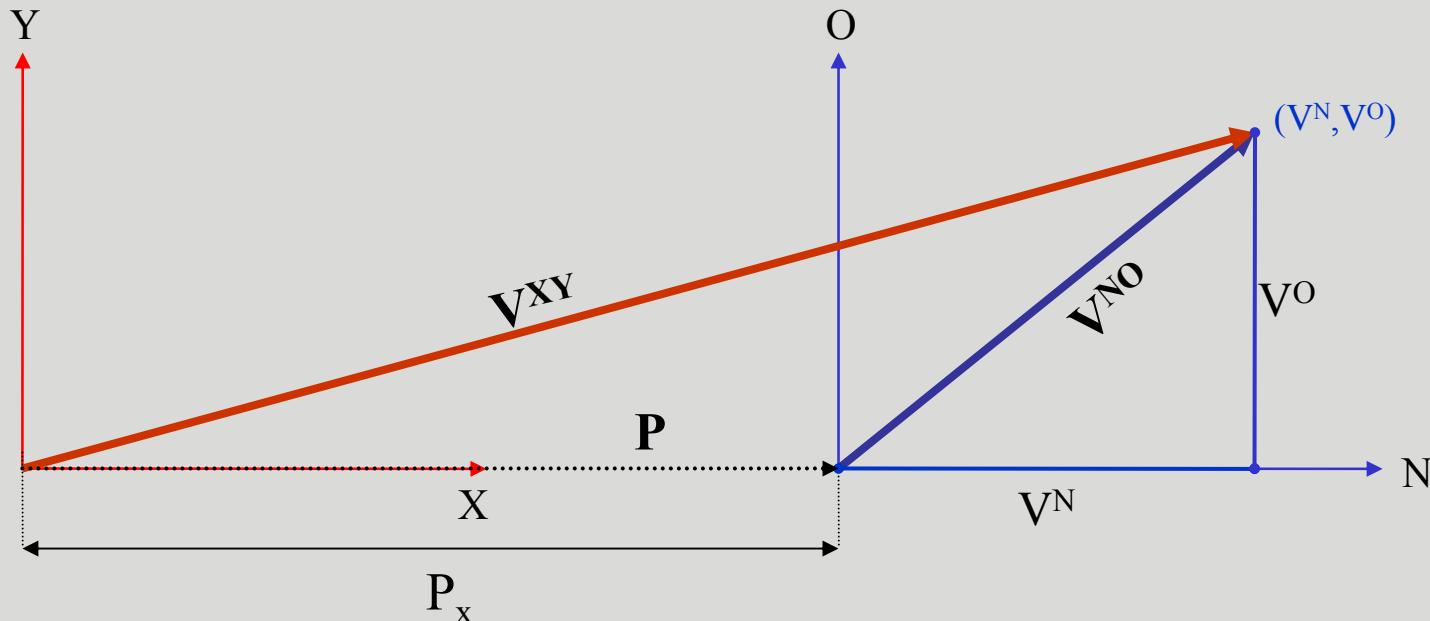
## Matrix Addition:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} + \begin{bmatrix} e & f \\ g & h \end{bmatrix} = \begin{bmatrix} (a + e) & (b + f) \\ (c + g) & (d + h) \end{bmatrix}$$

# Basic Transformations

## Moving Between Coordinate Frames

Translation Along the X-Axis

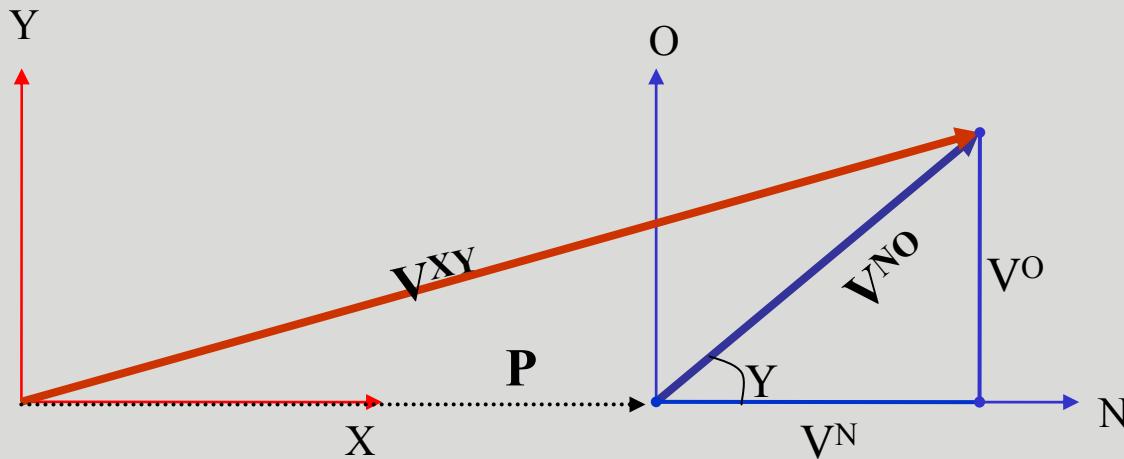


$P_x$  = distance between the XY and NO coordinate planes

Notation:

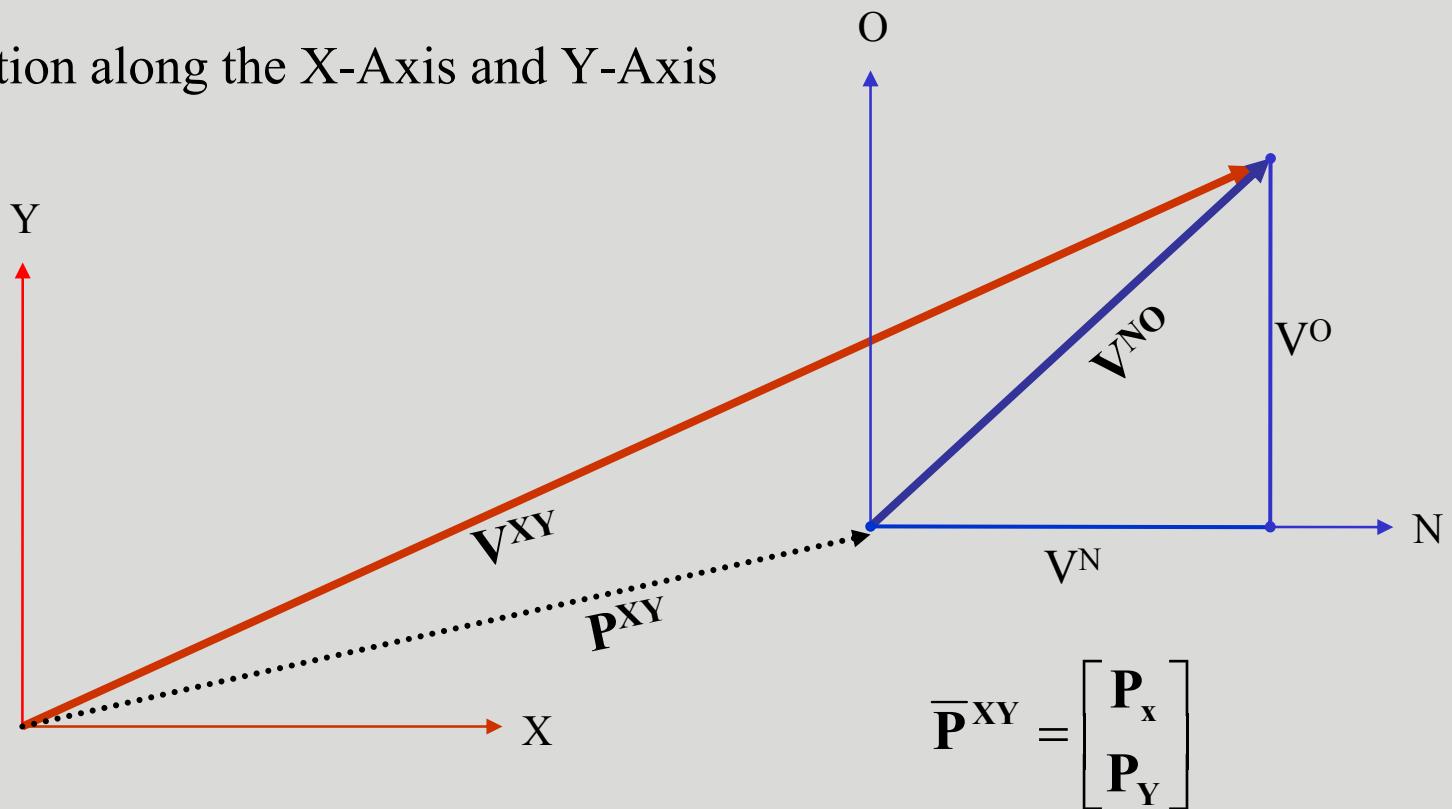
$$\bar{\mathbf{V}}^{XY} = \begin{bmatrix} \mathbf{V}^X \\ \mathbf{V}^Y \end{bmatrix} \quad \bar{\mathbf{V}}^{NO} = \begin{bmatrix} \mathbf{V}^N \\ \mathbf{V}^O \end{bmatrix} \quad \bar{\mathbf{P}} = \begin{bmatrix} \mathbf{P}_x \\ \mathbf{0} \end{bmatrix}$$

# Writing $\bar{V}^{XY}$ in terms of $\bar{V}^{NO}$



$$\bar{V}^{XY} = \begin{bmatrix} \mathbf{P}_X + \mathbf{V}^N \\ \mathbf{V}^O \end{bmatrix} = \bar{\mathbf{P}} + \bar{V}^{NO}$$

## Translation along the X-Axis and Y-Axis

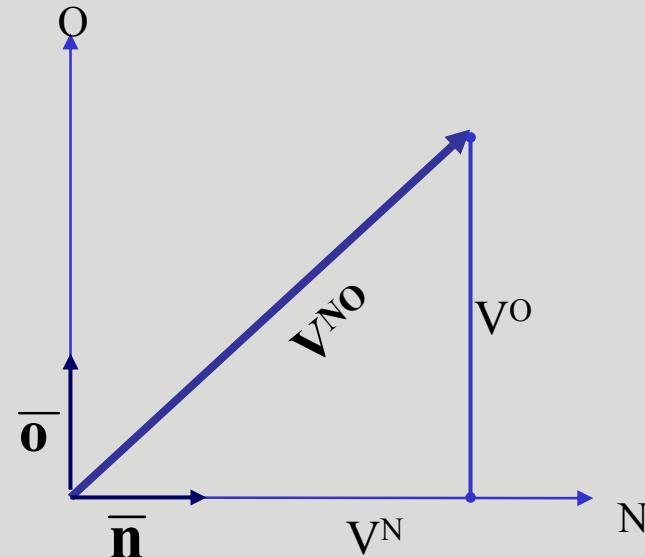


$$\bar{\mathbf{V}}^{XY} = \bar{\mathbf{P}} + \bar{\mathbf{V}}^{NO} = \begin{bmatrix} \mathbf{P}_x + \mathbf{V}^N \\ \mathbf{P}_y + \mathbf{V}^O \end{bmatrix}$$

# Using Basis Vectors

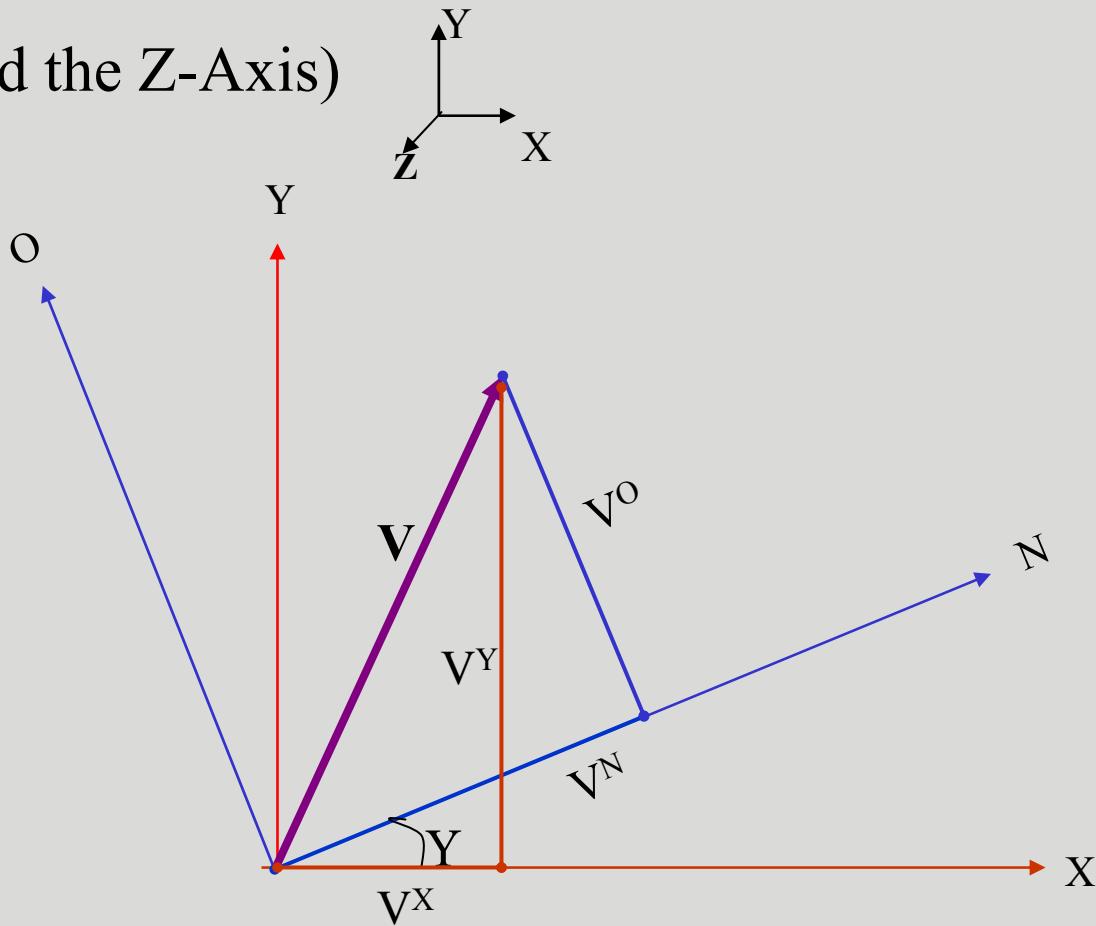
Basis vectors are unit vectors that point along a coordinate axis

- $\bar{n}$  Unit vector along the N-Axis
- $\bar{o}$  Unit vector along the O-Axis
- $\|V^{NO}\|$  Magnitude of the  $V^{NO}$  vector



$$\bar{V}^{NO} = \begin{bmatrix} V^N \\ V^O \end{bmatrix} = \begin{bmatrix} \|V^{NO}\| \cos \theta \\ \|V^{NO}\| \sin \theta \end{bmatrix} = \begin{bmatrix} \|V^{NO}\| \cos \theta \\ \|V^{NO}\| \cos(90 - \theta) \end{bmatrix} = \begin{bmatrix} \bar{V}^{NO} \cdot \bar{n} \\ \bar{V}^{NO} \cdot \bar{o} \end{bmatrix}$$

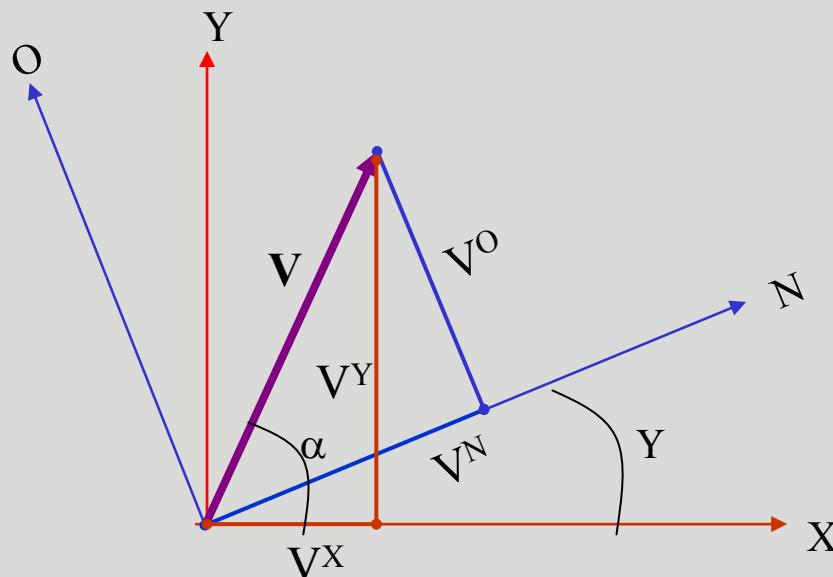
# Rotation (around the Z-Axis)



$Y$  = Angle of rotation between the XY and NO coordinate axis

$$\bar{V}^{XY} = \begin{bmatrix} V^X \\ V^Y \end{bmatrix}$$

$$\bar{V}^{NO} = \begin{bmatrix} V^N \\ V^O \end{bmatrix}$$



$\mathbf{x}$  Unit vector along X-Axis

$\Delta$  Can be considered with respect to the XY coordinates or NO coordinates

$$\|\bar{V}^{XY}\| = \|\bar{V}^{NO}\|$$

$$V^X = \|\bar{V}^{XY}\| \cos \alpha = \|\bar{V}^{NO}\| \cos \alpha = \bar{V}^{NO} \cdot \bar{x}$$

$$V^X = (V^N * \bar{n} + V^O * \bar{o}) \cdot \bar{x} \quad (\text{Substituting for } V^{NO} \text{ using the N and O components of the vector})$$

$$\begin{aligned} V^X &= V^N (\bar{x} \cdot \bar{n}) + V^O (\bar{x} \cdot \bar{o}) \\ &= V^N (\cos \theta) + V^O (\cos(\theta + 90)) \\ &= V^N (\cos \theta) - V^O (\sin \theta) \end{aligned}$$

Similarly....

$$\bar{V}^Y = \|\bar{V}^{NO}\| \sin \alpha = \|\bar{V}^{NO}\| \cos(90^\circ - \alpha) = \bar{V}^{NO} \bullet \bar{y}$$

$$\bar{V}^Y = (\bar{V}^N * \bar{n} + \bar{V}^O * \bar{o}) \bullet \bar{y}$$

$$\begin{aligned} \bar{V}^Y &= \bar{V}^N (\bar{y} \bullet \bar{n}) + \bar{V}^O (\bar{y} \bullet \bar{o}) \\ &= \bar{V}^N (\cos(90^\circ - \theta)) + \bar{V}^O (\cos \theta) \\ &= \bar{V}^N (\sin \theta) + \bar{V}^O (\cos \theta) \end{aligned}$$

So....

$$\bar{V}^X = \bar{V}^N (\cos \theta) - \bar{V}^O (\sin \theta)$$

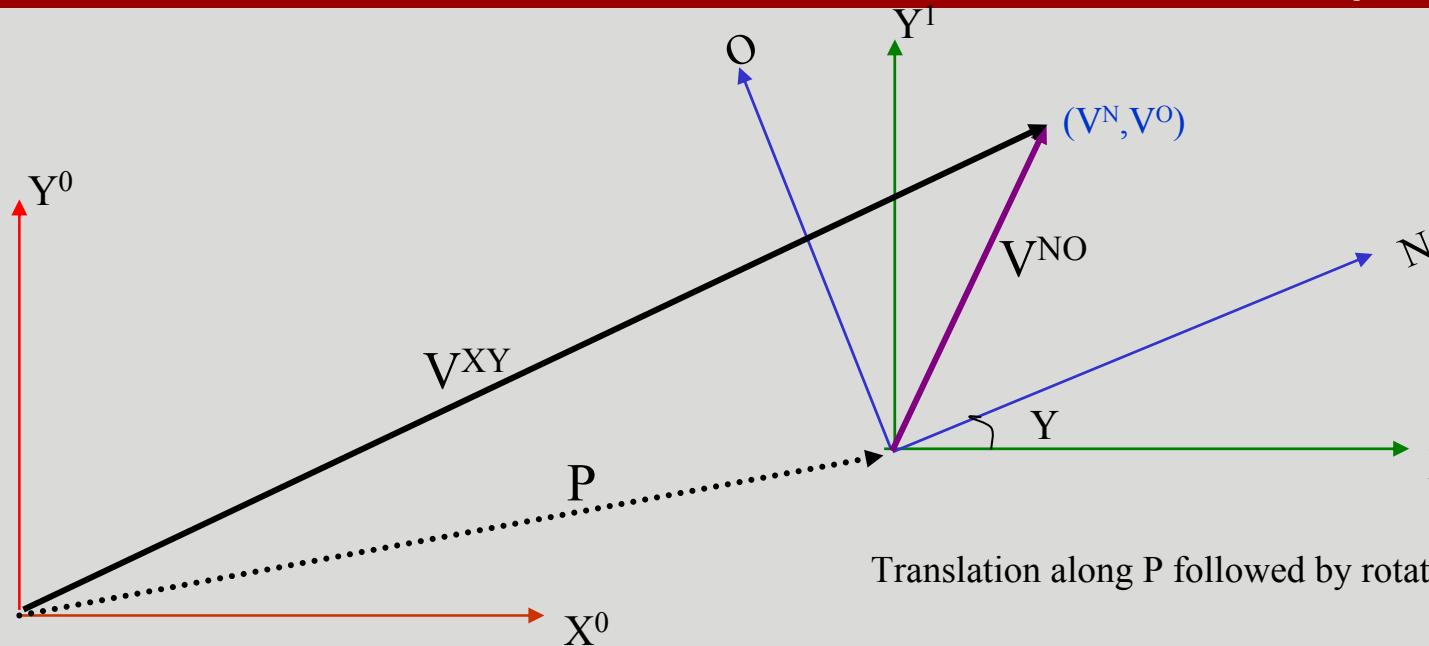
$$\bar{V}^Y = \bar{V}^N (\sin \theta) + \bar{V}^O (\cos \theta)$$

Written in Matrix Form

$$\bar{V}^{XY} = \begin{bmatrix} \bar{V}^X \\ \bar{V}^Y \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \bar{V}^N \\ \bar{V}^O \end{bmatrix}$$

$$\bar{V}^{XY} = \begin{bmatrix} \bar{V}^X \\ \bar{V}^Y \end{bmatrix}$$

Rotation Matrix about the z-axis



$$V^{XY} = \begin{bmatrix} V^X \\ V^Y \end{bmatrix} = \begin{bmatrix} P_x \\ P_y \end{bmatrix} + \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V^N \\ V^O \end{bmatrix}$$

(Note :  $P_x, P_y$  are relative to the original coordinate frame. **Translation** followed by **rotation** is different than **rotation** followed by **translation**.)

In other words, knowing the coordinates of a point  $(V^N, V^O)$  in some coordinate frame (NO) you can find the position of that point relative to your original coordinate frame  $(X^0Y^0)$ .

# HOMOGENEOUS REPRESENTATION

## Putting it all into a Matrix

$$\mathbf{V}^{XY} = \begin{bmatrix} \mathbf{V}^X \\ \mathbf{V}^Y \end{bmatrix} = \begin{bmatrix} \mathbf{P}_x \\ \mathbf{P}_y \end{bmatrix} + \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \mathbf{V}^N \\ \mathbf{V}^O \end{bmatrix}$$

What we found by doing a translation and a rotation

$$= \begin{bmatrix} \mathbf{V}^X \\ \mathbf{V}^Y \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{P}_x \\ \mathbf{P}_y \\ 1 \end{bmatrix} + \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{V}^N \\ \mathbf{V}^O \\ 1 \end{bmatrix}$$

Padding with 0's and 1's

$$= \begin{bmatrix} \mathbf{V}^X \\ \mathbf{V}^Y \\ 1 \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & \mathbf{P}_x \\ \sin \theta & \cos \theta & \mathbf{P}_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{V}^N \\ \mathbf{V}^O \\ 1 \end{bmatrix}$$

Simplifying into a matrix form

$$\mathbf{H} = \begin{bmatrix} \cos \theta & -\sin \theta & \mathbf{P}_x \\ \sin \theta & \cos \theta & \mathbf{P}_y \\ 0 & 0 & 1 \end{bmatrix}$$

Homogenous Matrix for a Translation in XY plane, followed by a Rotation around the z-axis

# Rotation Matrices in 3D – OK, let's return from

homogenous repn

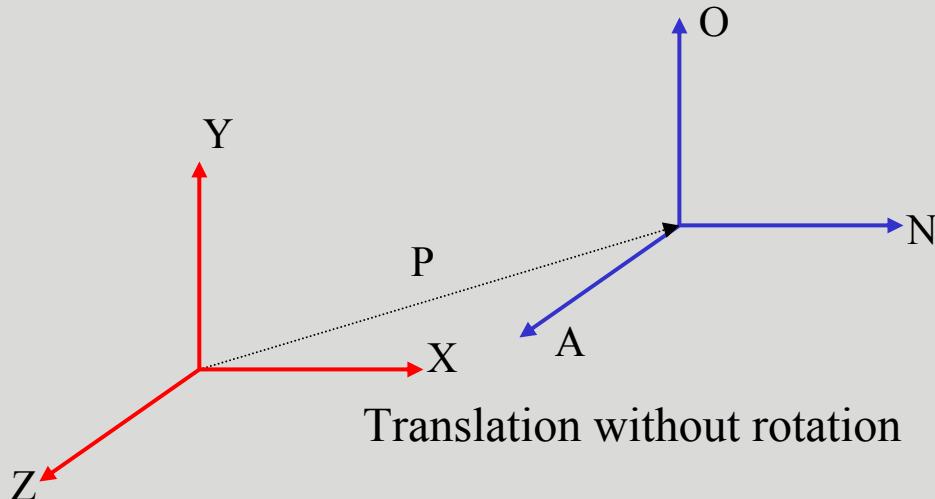
$$R_z = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{← Rotation around the Z-Axis}$$

$$R_y = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \quad \text{← Rotation around the Y-Axis}$$

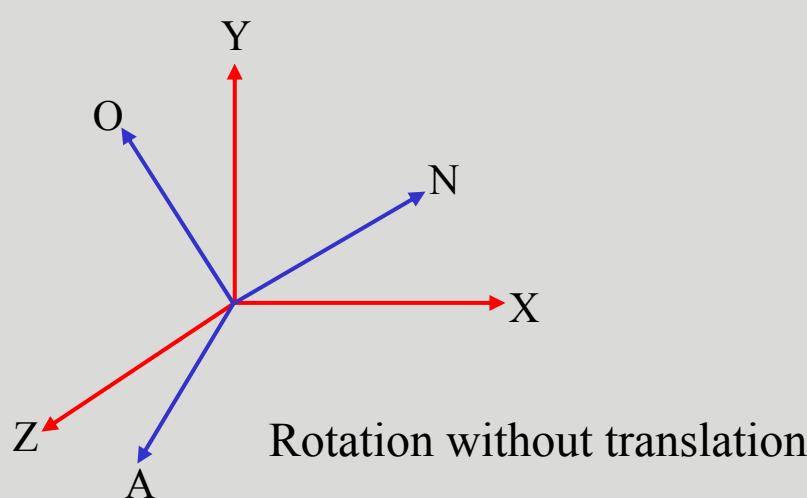
$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \quad \text{← Rotation around the X-Axis}$$

# Homogeneous Matrices in 3D

$H$  is a  $4 \times 4$  matrix that can describe a translation, rotation, or both in one matrix



$$H = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



$$H = \begin{bmatrix} n_x & o_x & a_x & 0 \\ n_y & o_y & a_y & 0 \\ n_z & o_z & a_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation part:

Could be rotation around z-axis, x-axis, y-axis or a combination of the three.

# Homogeneous Continued....

$$\mathbf{V}^{XY} = \mathbf{H} \begin{bmatrix} \mathbf{V}^N \\ \mathbf{V}^O \\ \mathbf{V}^A \\ 1 \end{bmatrix}$$

The (n,o,a) position of a point relative to the current coordinate frame you are in.

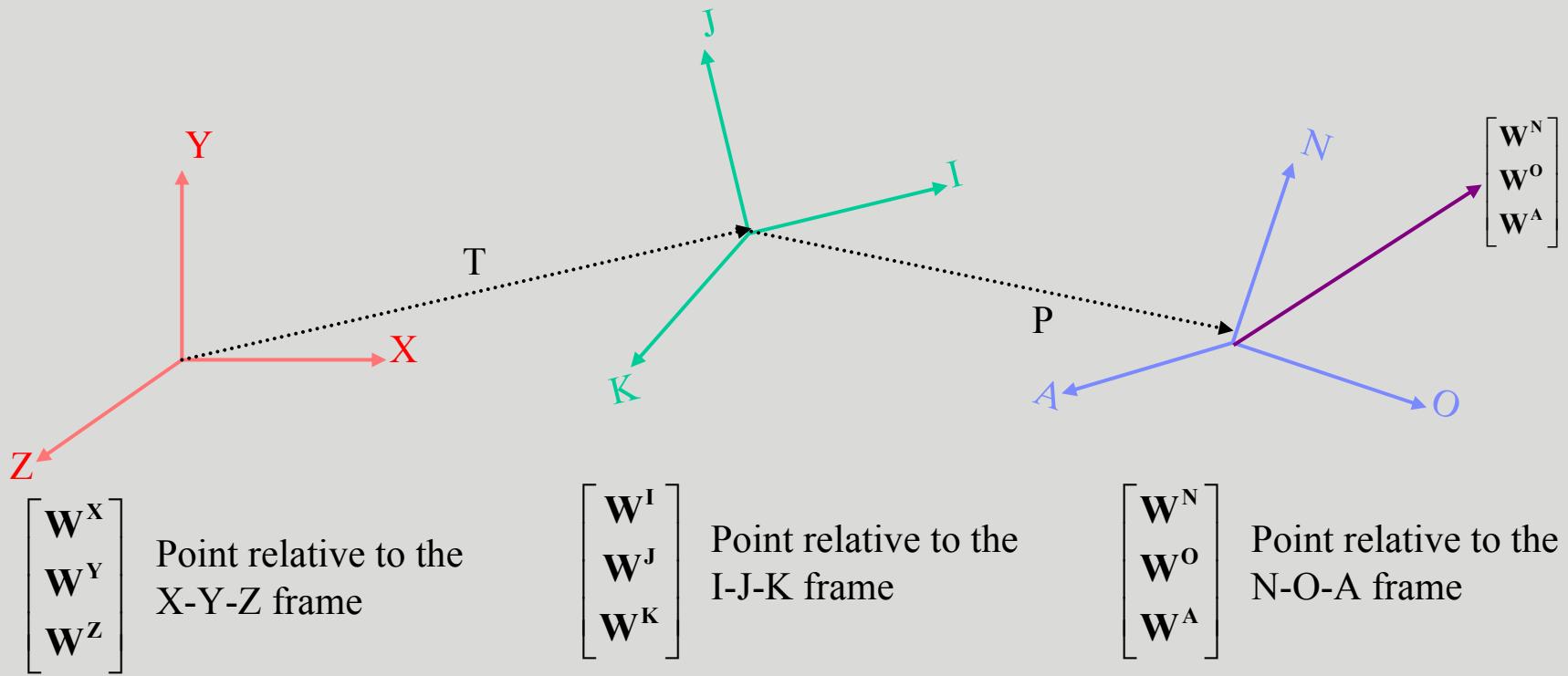
$$\mathbf{V}^{XY} = \begin{bmatrix} \mathbf{n}_x & \mathbf{o}_x & \mathbf{a}_x & \mathbf{P}_x \\ \mathbf{n}_y & \mathbf{o}_y & \mathbf{a}_y & \mathbf{P}_y \\ \mathbf{n}_z & \mathbf{o}_z & \mathbf{a}_z & \mathbf{P}_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{V}^N \\ \mathbf{V}^O \\ \mathbf{V}^A \\ 1 \end{bmatrix}$$

$$\mathbf{V}^X = \mathbf{n}_x \mathbf{V}^N + \mathbf{o}_x \mathbf{V}^O + \mathbf{a}_x \mathbf{V}^A + \mathbf{P}_x$$

The rotation and translation part can be combined into a single homogeneous matrix IF and ONLY IF both are relative to the same coordinate frame.

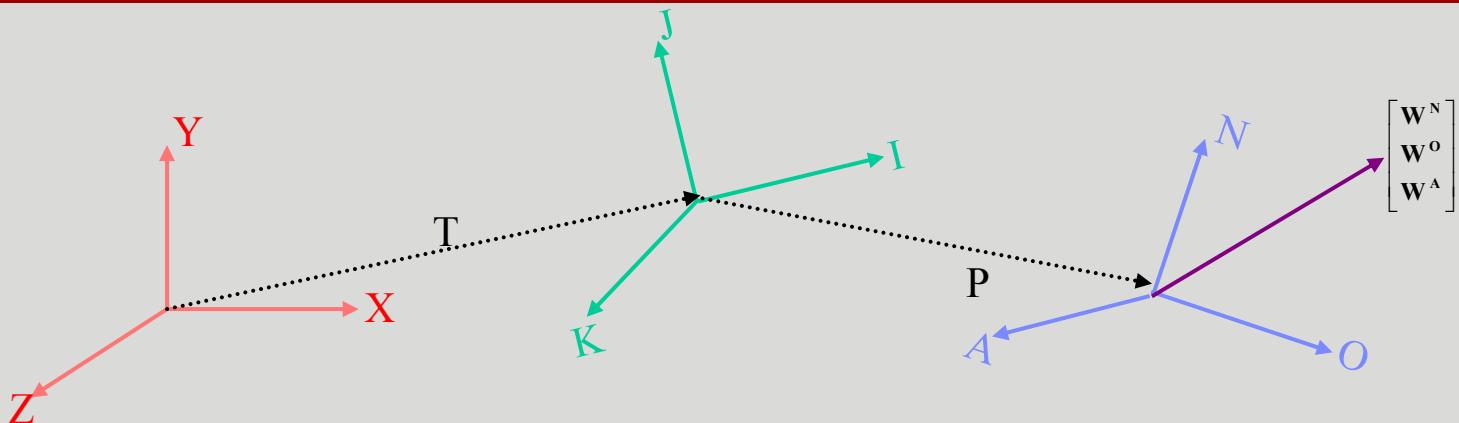
# Finding the Homogeneous Matrix

EX.



$$\begin{bmatrix} \mathbf{W}^I \\ \mathbf{W}^J \\ \mathbf{W}^K \end{bmatrix} = \begin{bmatrix} \mathbf{P}_i \\ \mathbf{P}_j \\ \mathbf{P}_k \end{bmatrix} + \begin{bmatrix} \mathbf{n}_i & \mathbf{o}_i & \mathbf{a}_i \\ \mathbf{n}_j & \mathbf{o}_j & \mathbf{a}_j \\ \mathbf{n}_k & \mathbf{o}_k & \mathbf{a}_k \end{bmatrix} \begin{bmatrix} \mathbf{W}^N \\ \mathbf{W}^O \\ \mathbf{W}^A \end{bmatrix}$$

$$\begin{bmatrix} \mathbf{W}^I \\ \mathbf{W}^J \\ \mathbf{W}^K \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{n}_i & \mathbf{o}_i & \mathbf{a}_i & \mathbf{P}_i \\ \mathbf{n}_j & \mathbf{o}_j & \mathbf{a}_j & \mathbf{P}_j \\ \mathbf{n}_k & \mathbf{o}_k & \mathbf{a}_k & \mathbf{P}_k \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{W}^N \\ \mathbf{W}^O \\ \mathbf{W}^A \\ 1 \end{bmatrix}$$



$$\begin{bmatrix} \mathbf{W}^X \\ \mathbf{W}^Y \\ \mathbf{W}^Z \end{bmatrix} = \begin{bmatrix} \mathbf{T}_x \\ \mathbf{T}_y \\ \mathbf{T}_z \end{bmatrix} + \begin{bmatrix} \mathbf{i}_x & \mathbf{j}_x & \mathbf{k}_x \\ \mathbf{i}_y & \mathbf{j}_y & \mathbf{k}_y \\ \mathbf{i}_z & \mathbf{j}_z & \mathbf{k}_z \end{bmatrix} \begin{bmatrix} \mathbf{W}^I \\ \mathbf{W}^J \\ \mathbf{W}^K \end{bmatrix}$$

$$\longrightarrow \begin{bmatrix} \mathbf{W}^X \\ \mathbf{W}^Y \\ \mathbf{W}^Z \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{i}_x & \mathbf{j}_x & \mathbf{k}_x & \mathbf{T}_x \\ \mathbf{i}_y & \mathbf{j}_y & \mathbf{k}_y & \mathbf{T}_y \\ \mathbf{i}_z & \mathbf{j}_z & \mathbf{k}_z & \mathbf{T}_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{W}^I \\ \mathbf{W}^J \\ \mathbf{W}^K \\ 1 \end{bmatrix}$$

Substituting for  $\begin{bmatrix} \mathbf{W}^I \\ \mathbf{W}^J \\ \mathbf{W}^K \end{bmatrix}$

$$\begin{bmatrix} \mathbf{W}^X \\ \mathbf{W}^Y \\ \mathbf{W}^Z \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{i}_x & \mathbf{j}_x & \mathbf{k}_x & \mathbf{T}_x \\ \mathbf{i}_y & \mathbf{j}_y & \mathbf{k}_y & \mathbf{T}_y \\ \mathbf{i}_z & \mathbf{j}_z & \mathbf{k}_z & \mathbf{T}_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{n}_i & \mathbf{o}_i & \mathbf{a}_i & \mathbf{P}_i \\ \mathbf{n}_j & \mathbf{o}_j & \mathbf{a}_j & \mathbf{P}_j \\ \mathbf{n}_k & \mathbf{o}_k & \mathbf{a}_k & \mathbf{P}_k \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{W}^N \\ \mathbf{W}^O \\ \mathbf{W}^A \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} \mathbf{W}^X \\ \mathbf{W}^Y \\ \mathbf{W}^Z \\ 1 \end{bmatrix} = \mathbf{H} \begin{bmatrix} \mathbf{W}^N \\ \mathbf{W}^O \\ \mathbf{W}^A \\ 1 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} \mathbf{i}_x & \mathbf{j}_x & \mathbf{k}_x & T_x \\ \mathbf{i}_y & \mathbf{j}_y & \mathbf{k}_y & T_y \\ \mathbf{i}_z & \mathbf{j}_z & \mathbf{k}_z & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{n}_i & \mathbf{o}_i & \mathbf{a}_i & P_i \\ \mathbf{n}_j & \mathbf{o}_j & \mathbf{a}_j & P_j \\ \mathbf{n}_k & \mathbf{o}_k & \mathbf{a}_k & P_k \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

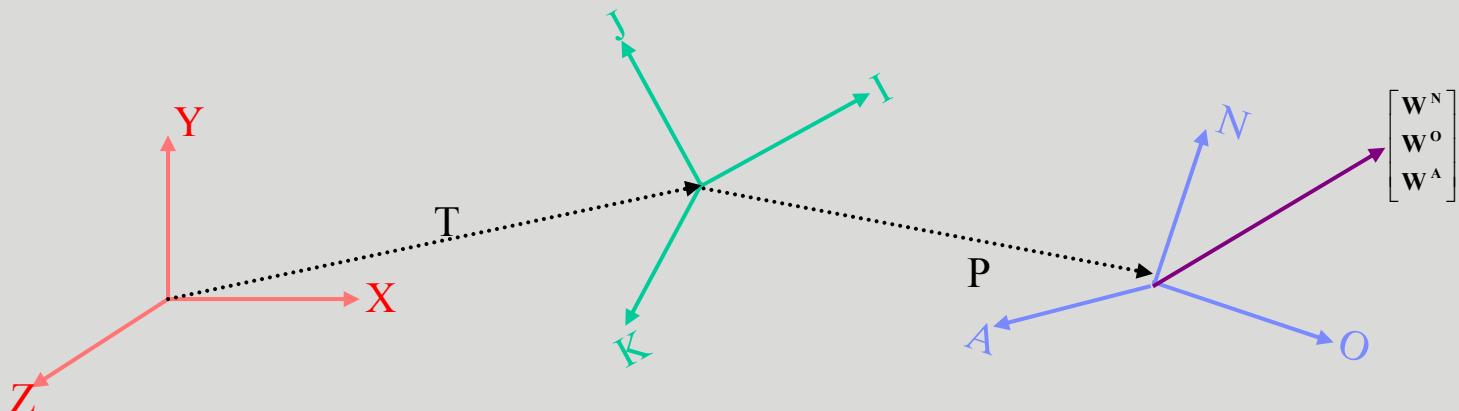
→ Product of the two matrices

Notice that  $\mathbf{H}$  can also be written as:

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{i}_x & \mathbf{j}_x & \mathbf{k}_x & 0 \\ \mathbf{i}_y & \mathbf{j}_y & \mathbf{k}_y & 0 \\ \mathbf{i}_z & \mathbf{j}_z & \mathbf{k}_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & P_i \\ 0 & 1 & 0 & P_j \\ 0 & 0 & 1 & P_k \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{n}_i & \mathbf{o}_i & \mathbf{a}_i & 0 \\ \mathbf{n}_j & \mathbf{o}_j & \mathbf{a}_j & 0 \\ \mathbf{n}_k & \mathbf{o}_k & \mathbf{a}_k & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$\mathbf{H} =$  (Translation relative to the XYZ frame) \* (Rotation relative to the XYZ frame)  
 \* (Translation relative to the IJK frame) \* (Rotation relative to the IJK frame)

# The Homogeneous Matrix is a concatenation of numerous translations and rotations



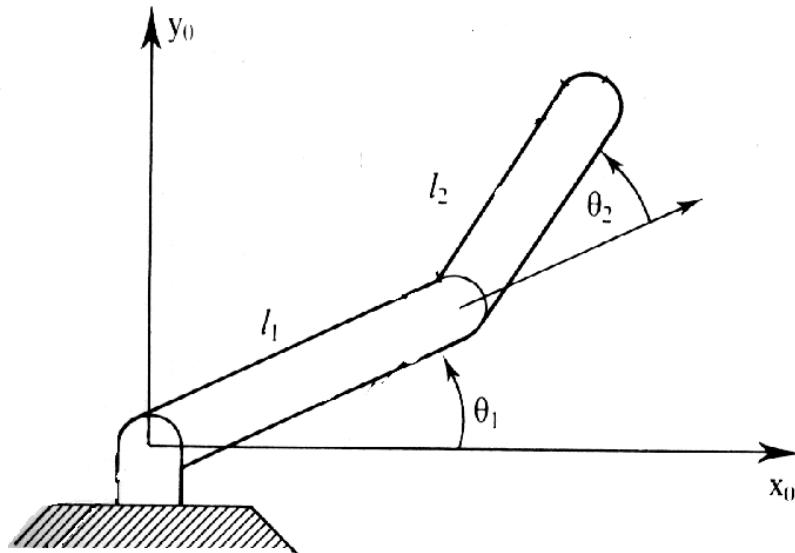
One more variation on finding H:

$H =$  (Rotate so that the X-axis is aligned with T)

- \* ( Translate along the new t-axis by  $\| T \|$  (magnitude of T))
- \* ( Rotate so that the t-axis is aligned with P)
- \* ( Translate along the p-axis by  $\| P \|$  )
- \* ( Rotate so that the p-axis is aligned with the O-axis)

This method might seem a bit confusing, but it's actually an easier way to solve our problem given the information we have. Here is an example...

# Forward Kinematics



## The Situation:

You have a robotic arm that starts out aligned with the  $x_0$ -axis. You tell the first link to move by  $Y_1$  and the second link to move by  $Y_2$ .

## The Quest:

What is the position of the end of the robotic arm?

### Solution:

#### 1. Geometric Approach

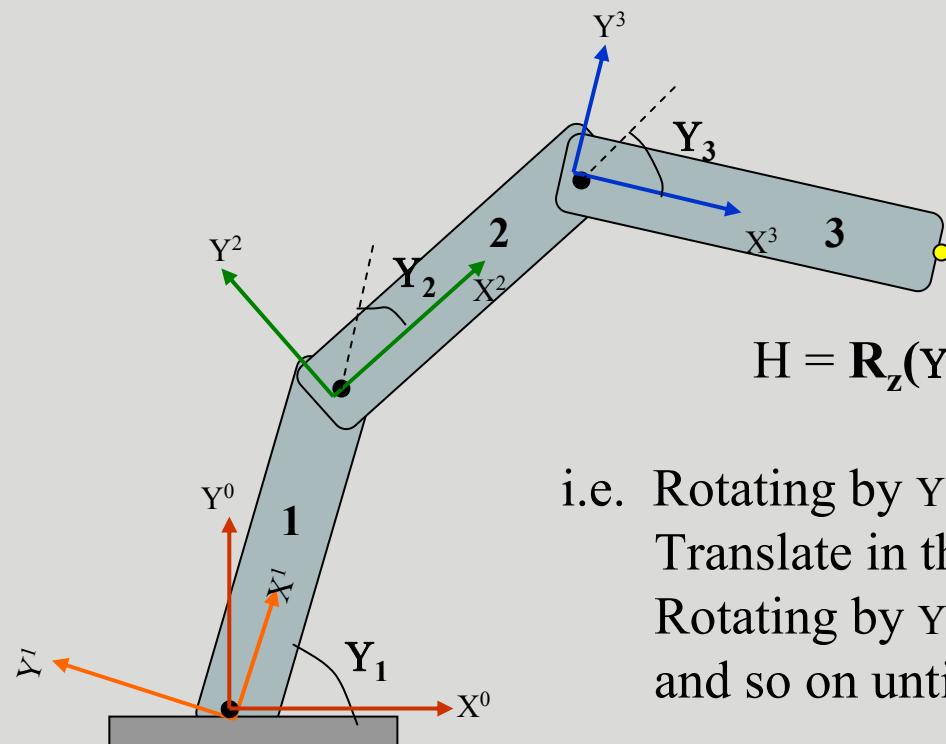
This might be the easiest solution for the simple situation. However, notice that the angles are measured relative to the direction of the previous link. (The first link is the exception. The angle is measured relative to its initial position.) For robots with more links and whose arm extends into 3 dimensions the geometry gets much more tedious.

#### 2. Algebraic Approach

Involves coordinate transformations.

## Example Problem:

You are have a three link arm that starts out aligned in the  $x$ -axis. Each link has lengths  $l_1, l_2, l_3$ , respectively. You tell the first one to move by  $Y_1$ , and so on as the diagram suggests. Find the Homogeneous matrix to get the position of the yellow dot in the  $X^0Y^0$  frame.



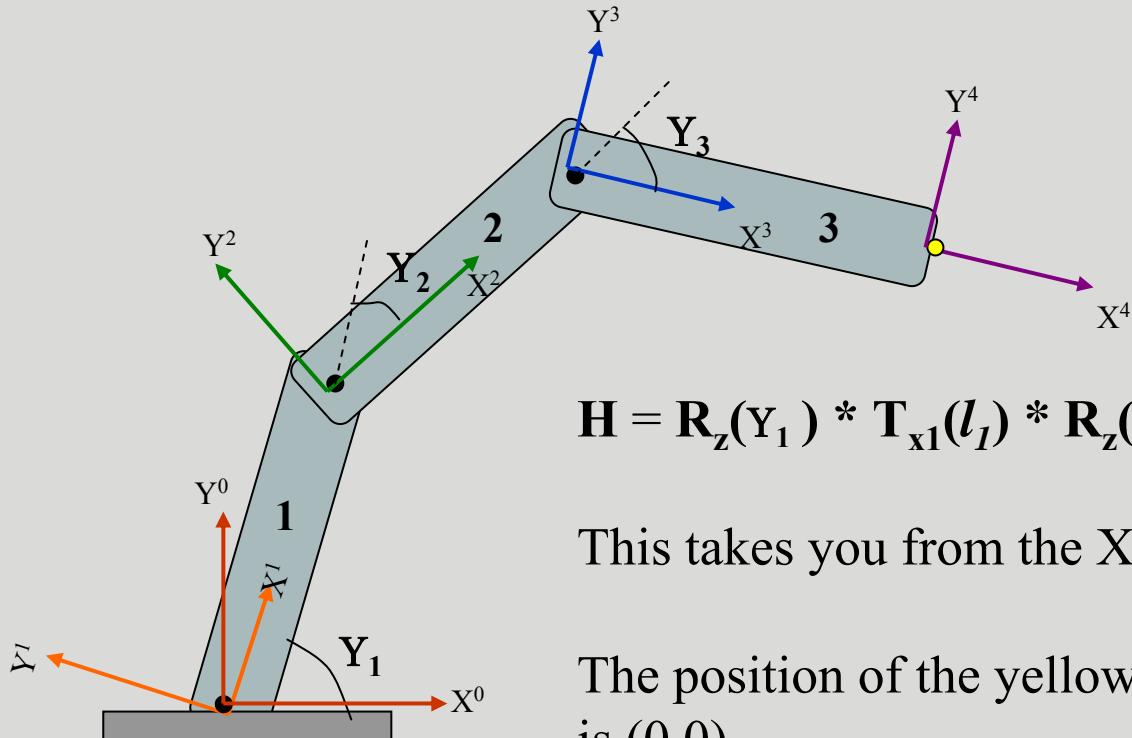
$$H = R_z(Y_1) * T_{x1}(l_1) * R_z(Y_2) * T_{x2}(l_2) * R_z(Y_3)$$

i.e. Rotating by  $Y_1$  will put you in the  $X^1Y^1$  frame.  
 Translate in the along the  $X^1$  axis by  $l_1$ .  
 Rotating by  $Y_2$  will put you in the  $X^2Y^2$  frame.  
 and so on until you are in the  $X^3Y^3$  frame.

The position of the yellow dot relative to the  $X^3Y^3$  frame is  $(l_1, 0)$ . Multiplying  $H$  by that position vector will give you the coordinates of the yellow point relative the the  $X^0Y^0$  frame.

Slight variation on the last solution:

Make the yellow dot the origin of a new coordinate  $X^4Y^4$  frame



$$H = R_z(Y_1) * T_{x1}(l_1) * R_z(Y_2) * T_{x2}(l_2) * R_z(Y_3) * T_{x3}(l_3)$$

This takes you from the  $X^0Y^0$  frame to the  $X^4Y^4$  frame.

The position of the yellow dot relative to the  $X^4Y^4$  frame is  $(0,0)$ .

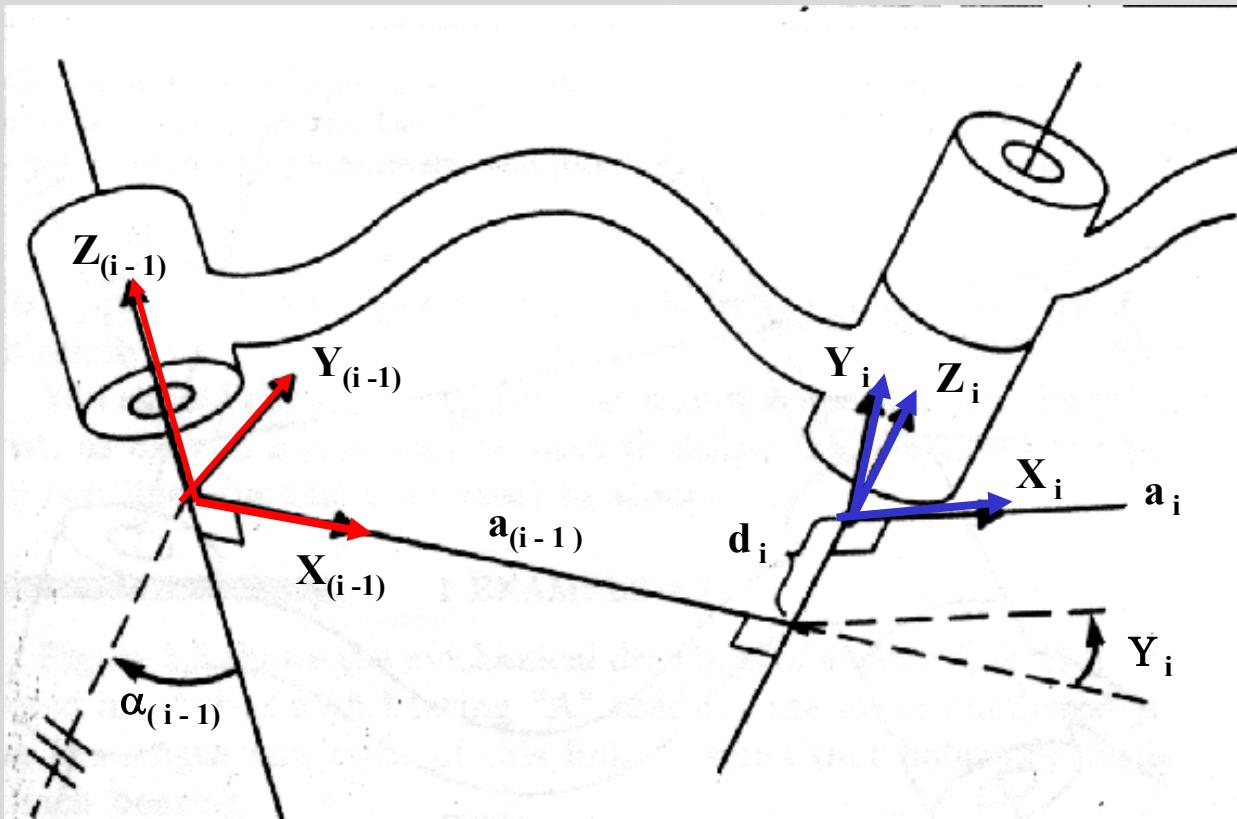
$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = H \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Notice that multiplying by the  $(0,0,0,1)$  vector will equal the last column of the  $H$  matrix.

More on Forward Kinematics...

Denavit - Hartenberg Parameters

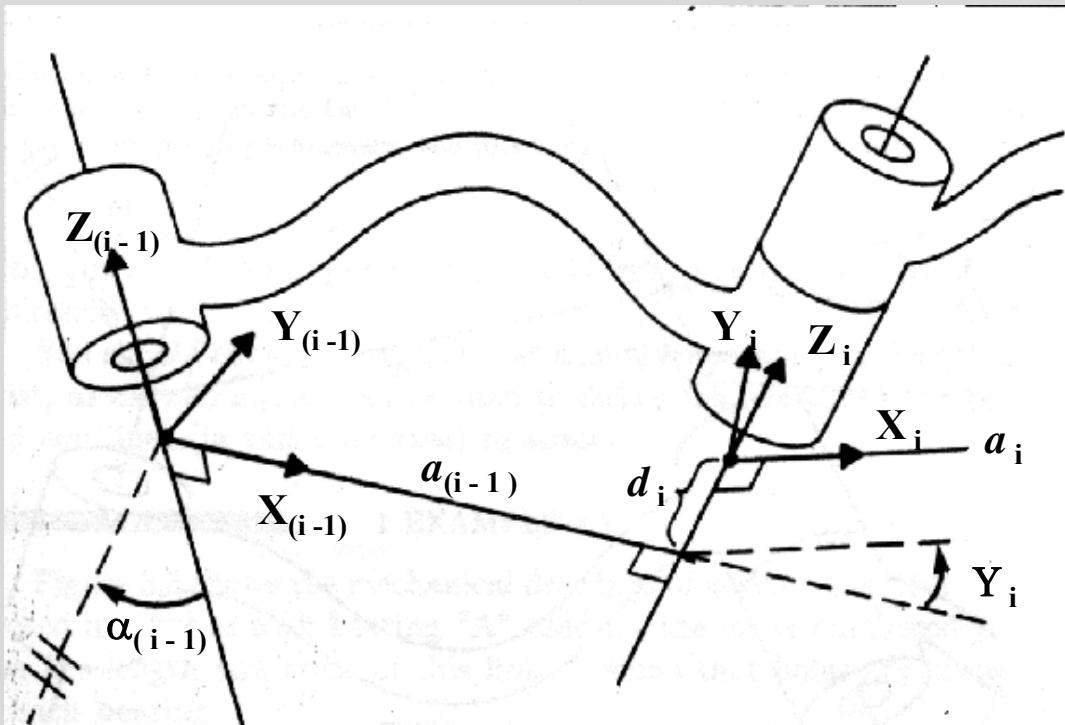
# Denavit-Hartenberg Notation



IDEA: Each joint is assigned a coordinate frame. Using the Denavit-Hartenberg notation, you need 4 parameters to describe how a frame ( $i$ ) relates to a previous frame ( $i - 1$ ).

THE PARAMETERS/VARIABLES:  $a, a', d, Y$

## The Parameters



You can align the two axis just using the 4 parameters

1)  $a_{(i-1)}$

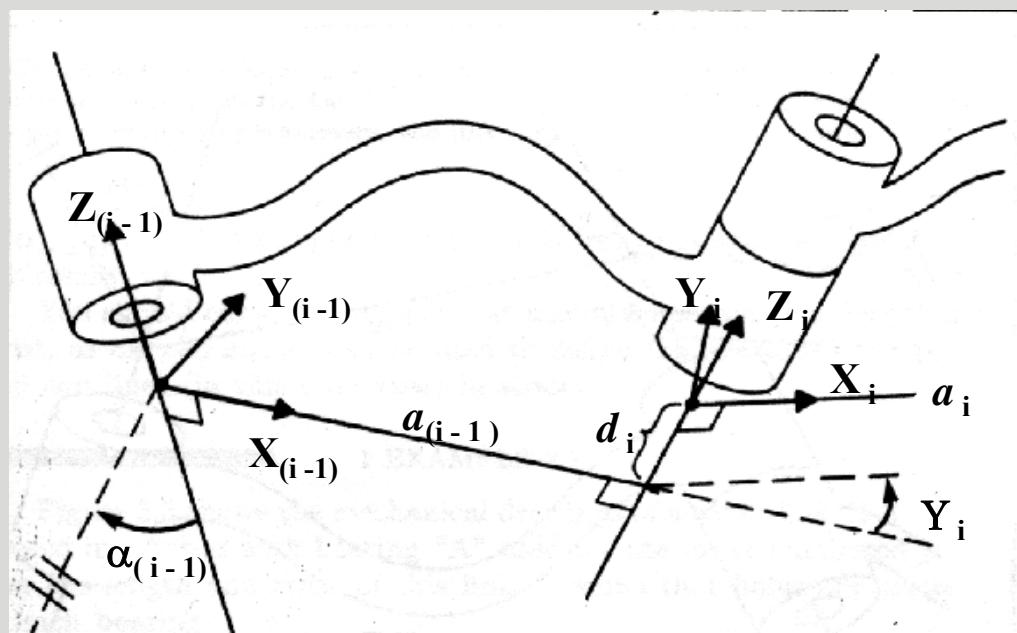
Technical Definition:  $a_{(i-1)}$  is the **length of the perpendicular** between the joint axes. The joint axes is the axes around which revolution takes place which are the  $Z_{(i-1)}$  and  $Z_{(i)}$  axes. These two axes can be viewed as lines in space. The common perpendicular is the shortest line between the two axis-lines and is perpendicular to both axis-lines.

***$a_{(i-1)}$  cont...***

Visual Approach - “A way to visualize the link parameter  $a_{(i-1)}$  is to imagine an expanding cylinder whose axis is the  $Z_{(i-1)}$  axis - when the cylinder just touches the joint axis  $i$  the radius of the cylinder is equal to  $a_{(i-1)}$ .” (Manipulator Kinematics)

It's Usually on the Diagram Approach - If the diagram already specifies the various coordinate frames, then the common perpendicular is usually the  $X_{(i-1)}$  axis. So  $a_{(i-1)}$  is just the displacement along the  $X_{(i-1)}$  to move from the  $(i-1)$  frame to the  $i$  frame.

If the link is prismatic, then  $a_{(i-1)}$  is a variable, not a parameter.



## 2) $\alpha_{(i-1)}$

Technical Definition: Amount of rotation around the common perpendicular so that the joint axes are parallel.

i.e. How much you have to rotate around the  $X_{(i-1)}$  axis so that the  $Z_{(i-1)}$  is pointing in the same direction as the  $Z_i$  axis. Positive rotation follows the right hand rule.

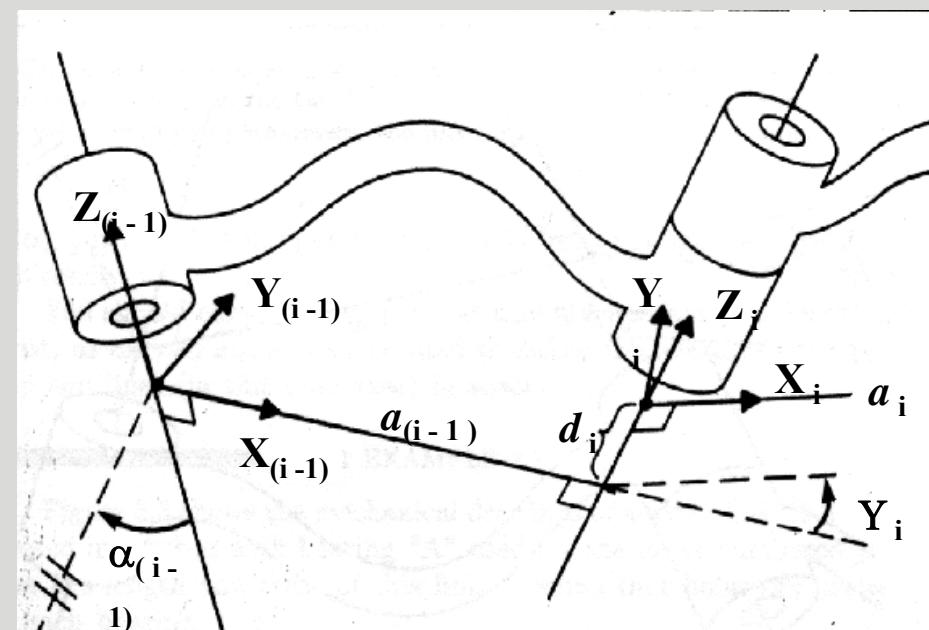
## 3) $d_{(i-1)}$

Technical Definition: The displacement along the  $Z_i$  axis needed to align the  $a_{(i-1)}$  common perpendicular to the  $a_i$  common perpendicular.

In other words, displacement along the  $Z_i$  to align the  $X_{(i-1)}$  and  $X_i$  axes.

## 4) $Y_i$

Amount of rotation around the  $Z_i$  axis needed to align the  $X_{(i-1)}$  axis with the  $X_i$  axis.

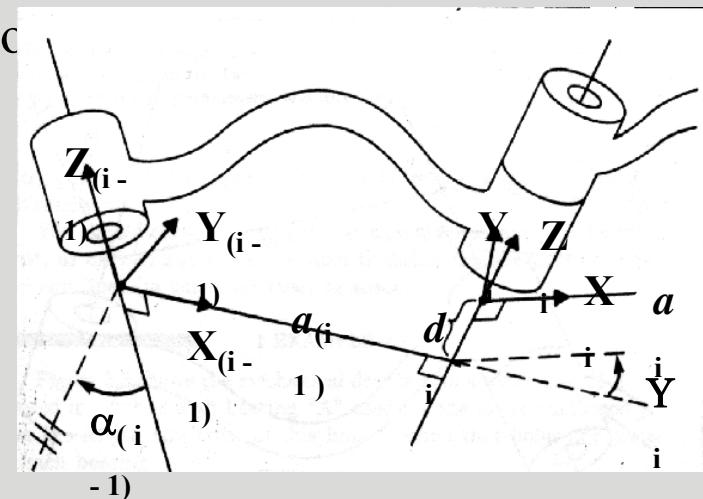


# The Denavit-Hartenberg Matrix

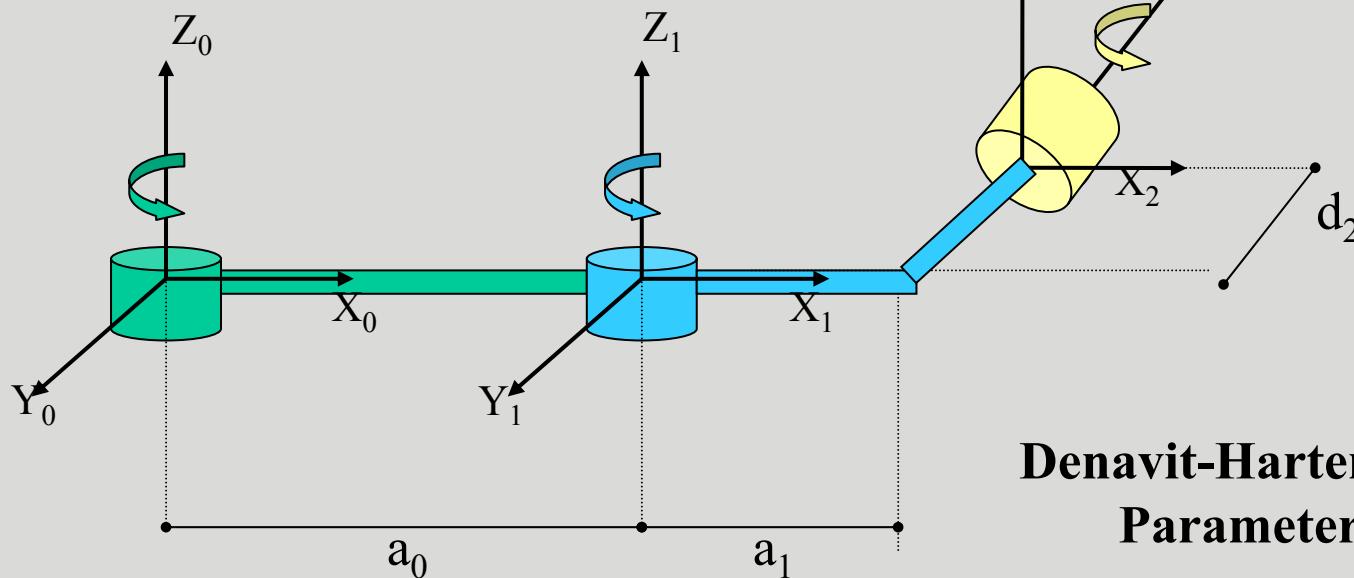
$$\begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{(i-1)} \\ \sin\theta_i \cos\alpha_{(i-1)} & \cos\theta_i \cos\alpha_{(i-1)} & -\sin\alpha_{(i-1)} & -\sin\alpha_{(i-1)} d_i \\ \sin\theta_i \sin\alpha_{(i-1)} & \cos\theta_i \sin\alpha_{(i-1)} & \cos\alpha_{(i-1)} & \cos\alpha_{(i-1)} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Just like the Homogeneous Matrix, the Denavit-Hartenberg Matrix is a transformation matrix from one coordinate frame to the next. Using a series of D-H Matrix multiplications and the D-H Parameter table, the final result is a transformation matrix from some frame to you.

Put the transformation here



# 3 Revolute Joints

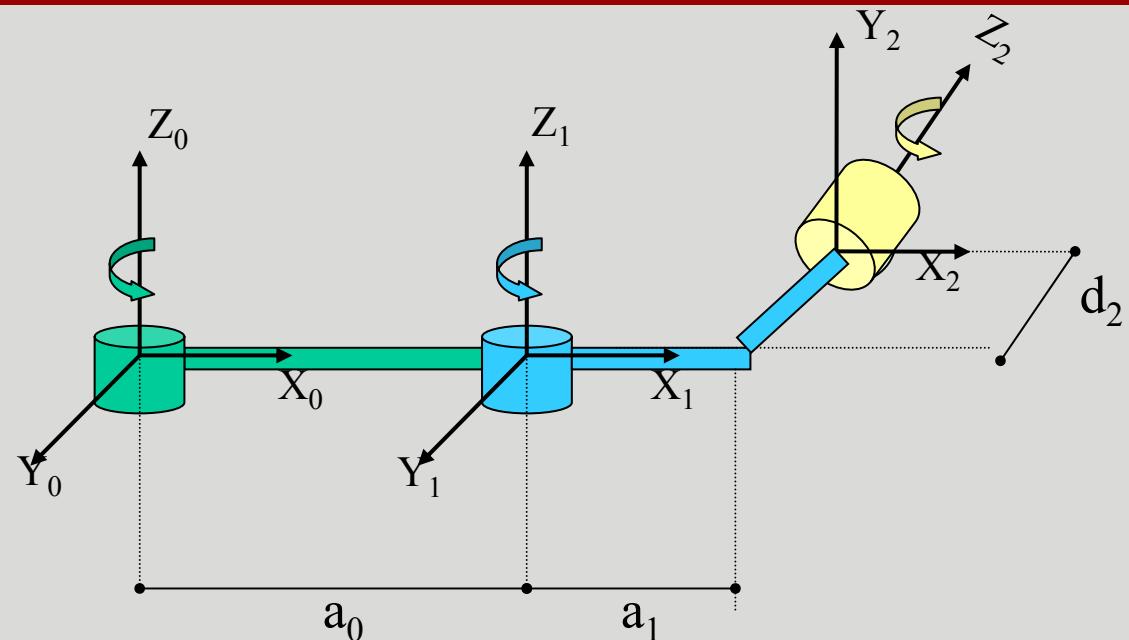


**Denavit-Hartenberg Link Parameter Table**

Notice that the table has two uses:

- 1) To describe the robot with its variables and parameters.
- 2) To describe some state of the robot by having a numerical values for the variables.

$i$	$\alpha_{(i-1)}$	$a_{(i-1)}$	$d_i$	$\theta_i$
0	0	0	0	$\theta_0$
1	0	$a_0$	0	$\theta_1$
2	-90	$a_1$	$d_2$	$\theta_2$



$i$	$\alpha_{(i-1)}$	$a_{(i-1)}$	$d_i$	$\theta_i$
0	0	0	0	$\theta_0$
1	0	$a_0$	0	$\theta_1$
2	-90	$a_1$	$d_2$	$\theta_2$

$$V^{X_0 Y_0 Z_0} = T \begin{bmatrix} V^{X_2} \\ V^{Y_2} \\ V^{Z_2} \\ 1 \end{bmatrix}$$

$$T = ({}^0 T) ({}^1 {}^0 T) ({}^2 {}^1 T)$$

Note:  $T$  is the D-H matrix with  $(i-1) = 0$  and  $i = 1$ .

$i$	$a_{(i-1)}$	$a_{(i-1)}$	$d_i$	$\theta_i$
0	0	0	0	$\theta_0$
1	0	$a_0$	0	$\theta_1$
2	-90	$a_1$	$d_2$	$\theta_2$

$${}^0\mathbf{T} = \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 & 0 & 0 \\ \sin\theta_0 & \cos\theta_0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This is just a rotation around the  $Z_0$  axis

$${}^0_1\mathbf{T} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & \mathbf{a}_0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

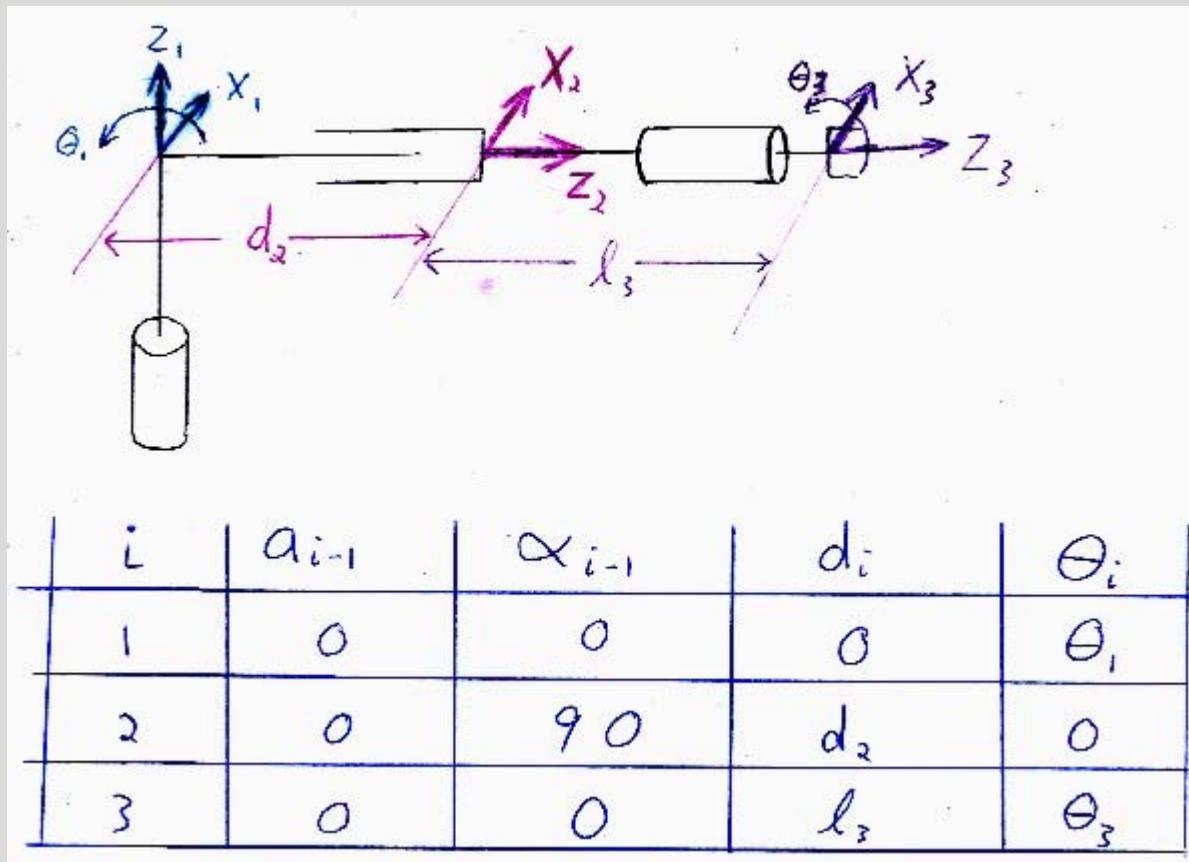
This is a translation by  $\mathbf{a}_0$  followed by a rotation around the  $Z_1$  axis

$${}^1_2\mathbf{T} = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & \mathbf{a}_1 \\ 0 & 0 & 1 & \mathbf{d}_2 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

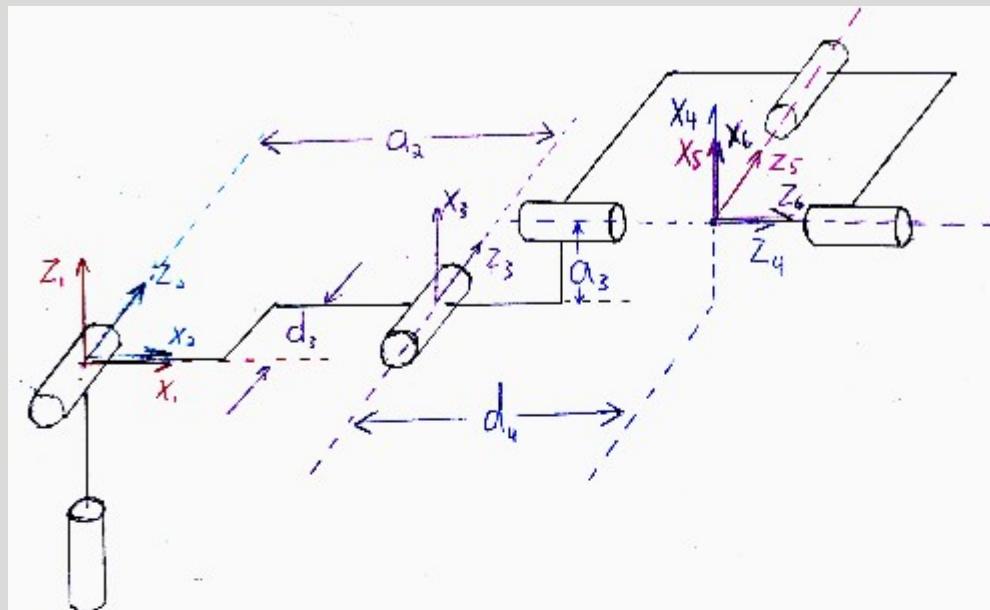
This is a translation by  $\mathbf{a}_1$  and then  $\mathbf{d}_2$  followed by a rotation around the  $X_2$  and  $Z_2$  axis

$$\mathbf{T} = ({}^0_0\mathbf{T})({}^0_1\mathbf{T})({}^1_2\mathbf{T})$$

# Next Example

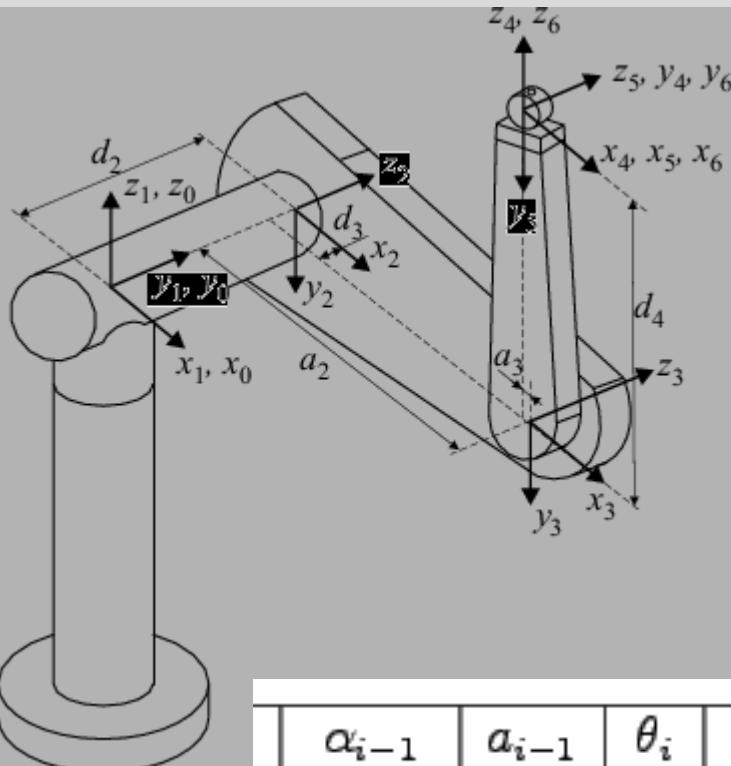


# Puma



$i$	$a_{i-1}$	$\alpha_{i-1}$	$d_i$	$\theta_i$
1	0	0	0	$\theta_1$
2	0	-90	0	$\theta_2$
3	$a_2$	0	$d_3$	$\theta_3$ ( $\theta_3 = 90^\circ$ in picture)
4	$a_3$	-90	$d_4$	$\theta_4$
5	0	90	0	$\theta_5$
6	0	-90	0	$\theta_6$

# Alternative PUMA 560



$\alpha_{i-1}$	$a_{i-1}$	$\theta_i$	$d_i$
0	0	$\theta_1$	0
$-\pi/2$	0	$\theta_2$	$d_2$
0	$a_2$	$\theta_3$	$d_3$
$\pi/2$	$a_3$	$\theta_4$	$d_4$
$-\pi/2$	0	$\theta_5$	0
$\pi/2$	0	$\theta_6$	0

$$T_1(\theta_1) = \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$T_2(\theta_2) = \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ -\sin \theta_2 & -\cos \theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$T_3(\theta_3) = \begin{pmatrix} \cos \theta_3 & -\sin \theta_3 & 0 & a_3 \\ \sin \theta_3 & \cos \theta_3 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$T_4(\theta_4) = \begin{pmatrix} \cos \theta_4 & -\sin \theta_4 & 0 & a_3 \\ 0 & 0 & -1 & -d_4 \\ \sin \theta_4 & \cos \theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$T_5(\theta_5) = \begin{pmatrix} \cos \theta_5 & -\sin \theta_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin \theta_5 & -\cos \theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

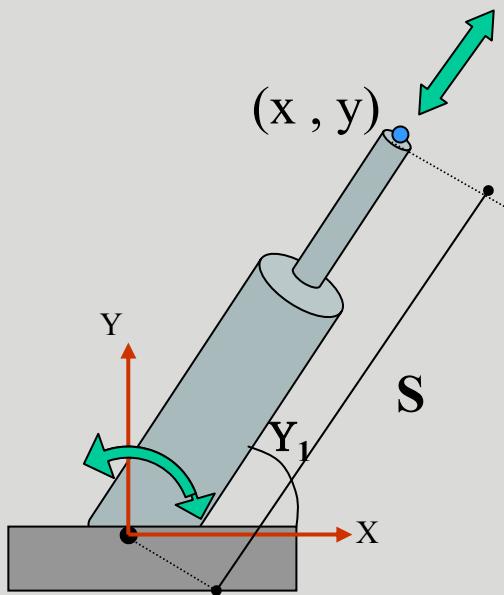
$$T_6(\theta_6) = \begin{pmatrix} \cos \theta_6 & -\sin \theta_6 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin \theta_6 & \cos \theta_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

# Inverse Kinematics

From Position to Angles

# A Simple Example

Revolute and  
Prismatic Joints  
Combined



Finding Y:

$$\theta = \arctan\left(\frac{y}{x}\right)$$

More Specifically:

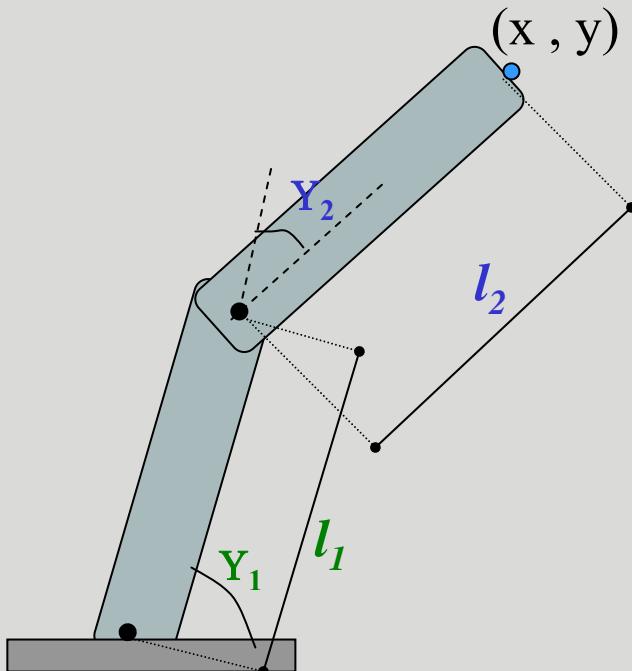
$$\theta = \arctan 2\left(\frac{y}{x}\right)$$

`arctan2()` specifies that it's in the first quadrant

Finding S:

$$S = \sqrt{(x^2 + y^2)}$$

# Inverse Kinematics of a Two Link Manipulator

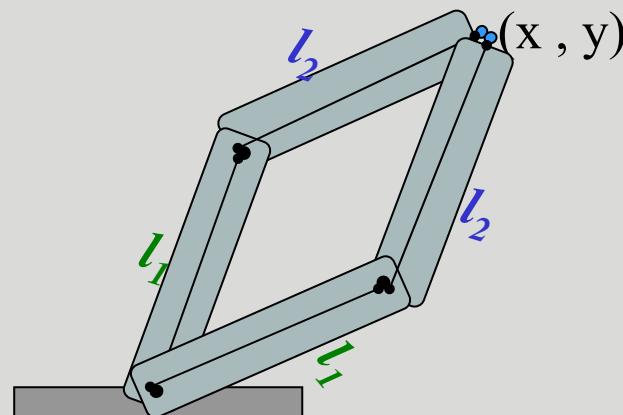


Given:  $l_1, l_2, x, y$

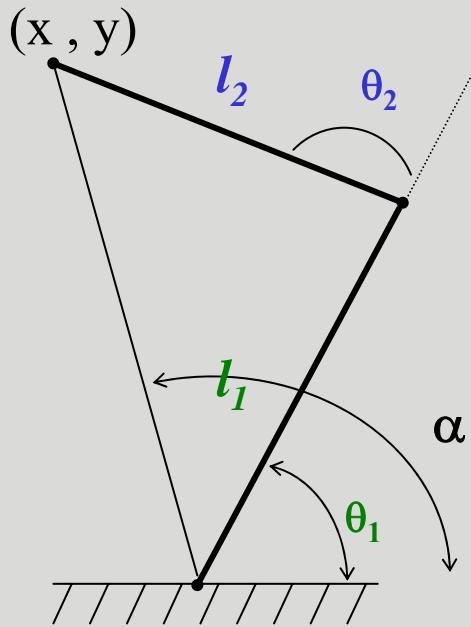
Find:  $Y_1, Y_2$

Redundancy:

A unique solution to this problem does not exist. Notice, that using the “givens” two solutions are possible. Sometimes no solution is possible.



# The Geometric Solution



Using the Law of Cosines:

$$\frac{\sin B}{b} = \frac{\sin C}{c}$$

$$\frac{\sin \bar{\theta}_1}{l_2} = \frac{\sin(180 - \theta_2)}{\sqrt{x^2 + y^2}} = \frac{\sin(\theta_2)}{\sqrt{x^2 + y^2}}$$

$$\theta_1 = \alpha - \bar{\theta}_1$$

$$\alpha = \arctan 2\left(\frac{y}{x}\right)$$

Using the Law of Cosines:

$$c^2 = a^2 + b^2 - 2ab \cos C$$

$$(x^2 + y^2) = l_1^2 + l_2^2 - 2l_1 l_2 \cos(180 - \theta_2)$$

$$\cos(180 - \theta_2) = -\cos(\theta_2)$$

$$\cos(\theta_2) = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1 l_2}$$

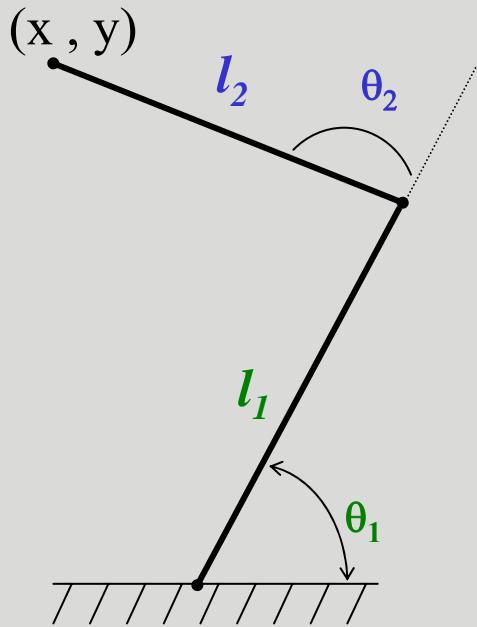
$$\theta_2 = \arccos\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1 l_2}\right)$$

Redundant since  $\theta_2$  could be in the first or fourth quadrant.

Redundancy caused since  $\theta_2$  has two possible values

$$\theta_1 = \arctan 2\left(\frac{y}{x}\right) - \arcsin\left(\frac{l_2 \sin(\theta_2)}{\sqrt{x^2 + y^2}}\right)$$

# The Algebraic Solution



$$c_1 = \cos \theta_1$$

$$c_{1+2} = \cos(\theta_2 + \theta_1)$$

$$(1) \ x = l_1 c_1 + l_2 c_{1+2}$$

$$(2) \ y = l_1 s_1 + l_2 \sin_{1+2}$$

$$(1)^2 + (2)^2 = x^2 + y^2 =$$

$$= \left( l_1^2 c_1^2 + l_2^2 (c_{1+2})^2 + 2l_1 l_2 c_1 (c_{1+2}) \right) + \left( l_1^2 s_1^2 + l_2^2 (\sin_{1+2})^2 + 2l_1 l_2 s_1 (\sin_{1+2}) \right)$$

$$= l_1^2 + l_2^2 + 2l_1 l_2 (c_1 (c_{1+2}) + s_1 (\sin_{1+2}))$$

$$= l_1^2 + l_2^2 + 2l_1 l_2 c_2 \quad \text{Only Unknown}$$

$$\therefore \theta_2 = \arccos \left( \frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1 l_2} \right)$$

Note:

$$\cos(a \pm b) = (\cos a)(\cos b) \mp (\sin a)(\sin b)$$

$$\sin(a \pm b) = (\cos a)(\sin b) \pm (\cos b)(\sin a)$$

$$\begin{aligned}
 x &= l_1 c_1 + l_2 c_{1+2} \\
 &= l_1 c_1 + l_2 c_1 c_2 - l_2 s_1 s_2 \\
 &= c_1(l_1 + l_2 c_2) - s_1(l_2 s_2)
 \end{aligned}$$

Note:

$$\begin{aligned}
 \cos(a \pm b) &= (\cos a)(\cos b) \mp (\sin a)(\sin b) \\
 \sin(a \pm b) &= (\cos a)(\sin b) \pm (\cos b)(\sin a)
 \end{aligned}$$

$$\begin{aligned}
 y &= l_1 s_1 + l_2 \sin_{1+2} \\
 &= l_1 s_1 + l_2 s_1 c_2 + l_2 s_2 c_1 \\
 &= c_1(l_2 s_2) + s_1(l_1 + l_2 c_2)
 \end{aligned}$$

$$c_1 = \frac{x + s_1(l_2 s_2)}{(l_1 + l_2 c_2)}$$

$$y = \frac{x + s_1(l_2 s_2)}{(l_1 + l_2 c_2)}(l_2 s_2) + s_1(l_1 + l_2 c_2)$$

$$= \frac{1}{(l_1 + l_2 c_2)} \left( x l_2 s_2 + s_1(l_1^2 + l_2^2 + 2 l_1 l_2 c_2) \right)$$

We know what  $\theta_2$  is from the previous slide. We need to solve for  $\theta_1$ . Now we have two equations and two unknowns ( $\sin \theta_1$  and  $\cos \theta_1$ )

Substituting for  $c_1$  and simplifying many times

Notice this is the law of cosines and can be replaced by  $x^2 + y^2$

$$s_1 = \frac{y(l_1 + l_2 c_2) - x l_2 s_2}{x^2 + y^2}$$

$$\theta_1 = \arctan 2(s_1, c_1)$$